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Abstract

This report describes the features of Aspen-EE (Electricity Enhancement), a new model for simulating the interdependent effects of market decisions and disruptions in the electric power system on other critical infrastructures in the U.S. economy. Aspen-EE extends and modifies the capabilities of Aspen, an agent-based model previously developed by Sandia National Laboratories. Aspen-EE was tested on a series of scenarios in which the rules governing electric power trades were changed. Analysis of the scenario results indicates that the power generation company agents will adjust the quantity of power bid into each market as a function of the market rules. Results indicate that when two power markets are faced with identical economic circumstances, the traditionally higher-priced market sees its market clearing price decline, while the traditionally lower-priced market sees a relative increase in market clearing price. These results indicate that Aspen-EE is predicting power market trends that are consistent with expected economic behavior.

Acknowledgments

We would like to extend our appreciation to Dr. Richard Pryor, the creator of Aspen, who has worked with us in developing Aspen-EE and to Mike Griesmeyer for his important work in porting the original Aspen logic to a C++ platform, which was essential in the completion of this work.

Contents

Figures

Tables

Nomenclature

Aspen	(an agent-based simulation model of the U.S. economy)
CAL-ISO	California Independent System Operator
CALPX	California Power Exchange
EE	Electricity Enhancement
FuelCo	fuel company agent
GALCS	genetic algorithm learning classifier system
GenCo	generation company agent
ISO	independent system operator
LDRD	Laboratory Directed Research and Development (a Sandia program)
MCP	market clearing price
MPI	Message Passing Interface
MW	megawatt
Sandia	Sandia National Laboratories

Aspen-EE: An Agent-Based Model of Infrastructure Interdependency

Introduction

As individuals and as a nation, we depend on critical infrastructures in the United States to provide essential services that support (among other things) our economic prosperity and quality of life [1]. These critical infrastructures include electric power systems, banking and finance, transportation, telecommunications, water supply systems, gas and oil storage, emergency services, and government [2]. Historically, these infrastructures have been vulnerable to malevolent acts and to natural disasters. Today, however, the latest threat arises from the increasing complexity of the individual infrastructures and their growing interconnectedness with each other. While on balance this added connectivity will improve our nation's economic efficiency, the increased coupling between and among infrastructures could also result in situations where a disturbance in a formerly isolated infrastructure unexpectedly cascades across diverse infrastructures. Previous experience has shown that a loss of service in one infrastructure element can produce indirect but potentially severe problems, both physical and economic, to elements of other infrastructures. Therefore, an understanding of the behavior of complex infrastructures, each a system of complex interdependent elements, can be critical to understanding and predicting infrastructure responses to unexpected disturbances. Importantly, the added connectivity has created new interdependencies and the consequent possibility of unforeseen vulnerabilities [3].

To better understand infrastructure interdependency and the results of unexpected Events, Sandia National Laboratories (Sandia) has developed a new model using our unique microsimulation approach. This model, called Aspen-Electricity Enhancement (EE), is an extension and modification of a model of the U.S. economy called Aspen, also developed by Sandia. Aspen is a Monte Carlo simulation that uses agents to represent various decision-making segments in the economy, such as banks, households, industries, and the Federal Reserve. And, through the use of evolutionary learning techniques, Aspen allows us to examine the interactive behavior of these agents as they make real-life decisions in an environment where agents communicate with each other and adapt their behaviors to changing economic conditions, as they learn from their past experience [4].

Aspen-EE builds on the Aspen model but takes a somewhat different focus. With Aspen-EE, the primary area of interest is the impact of market structures and power outages in the electric power system, a critical infrastructure, on other infrastructures in the economy. Thus, Aspen-EE includes additional agents that represent the major players and processes in the electric power system—producers of electricity, market structures that control the production of electricity, and a supplier of electric utility requirements.

This report describes the agent interactions and decision-making processes available in Aspen-EE and shows through a set of sample scenarios how this model can be used to examine issues of timely concern in the electric power system. Detailed information on user input to Aspen-EE is also provided. To highlight the infrastructure interdependency, we have chosen to model market activity resulting from restructuring efforts in the electric power system, as briefly discussed next.

The Changing Face of the Electric Power System

The electric power system in the United States is undergoing extensive restructuring—from a regulated monopoly to a competitive market system [5, 6]. Historically, the system was composed mainly of vertically integrated, full-service utilities that were investor-owned and state-regulated. Each utility was responsible for generating, transmitting, and distributing power to its customers at rates set by state regulatory bodies. In the past few years, however, both federal and state legislation have impacted the way these utilities conduct business. Restructuring plans in 24 states and the District of Columbia are already in place, and nearly all the other states are considering restructuring proposals [6, 7].

Though often termed "deregulation," current restructuring efforts are actually deregulating only the generation aspect of the industry. The transmission and distribution of power, as well as the approval of new facilities remain under regulatory authority control in states that have implemented plans for restructuring [6]. In many state legislative actions on restructuring, utilities have been required to sell their generation assets and buy electricity from other power providers in the open marketplace to satisfy customer demand.

In Aspen-EE, the problem of interest focuses on the internal actions and the external effects of short-term electric power markets—markets similar to those set up in California as a result of restructuring. For example, the California Independent System Operator (Cal-ISO) is the controller of the state's power grid and, in conjunction with the California Power Exchange (CalPX), offers open-competition markets for energy traders in the final hours before energy is consumed [8]. As originally envisioned, short-term markets were designed to deal with a minimal amount of daily transactions relative to long-term markets(2–3 percent, for example). The reality, though, in some states has been quite different; short-term markets are often meeting 20 percent or more of demand, especially at times of peak demand for a market territory. These short term markets have displayed wild price volatility affecting the consumers of power (who are used to paying steady rates) in dramatic ways and leading responsible institutional entities to institute measures like price caps to keep costs down. The institution of price caps has the potential to lead to market shortages (and thus power outages) in a region, if companies who generate power can sell their power in other market regions which either have a higher price cap or none at all.

The Model

The development of Aspen-EE was funded by Sandia's Laboratory Directed Research and Development (LDRD) program. In building Aspen-EE, we used the agent-based model Aspen as the foundation and ENERGY 2020 as a primary reference for learning about the behavior of electric power agents. ENERGY 2020 is a dynamic model of the North American electric and gas utilities that simulates market, financial, technological change, physical production, and transmission dynamics.

Agent-based models assume that complex behavior emerges from many individual, relatively simple interactions rather than from the complexity inherent in any particular agent. Agents have simple rules of behavior and react to their environment (i.e., the other agents and any static features) without reference to any global goals—in other words, the agents are undertaking purely local transactions. The net results of these local interactions and decisions are phenomena that emerge on a global level. When unexpected results emerge from the simulation, it is important to be confident that we understand the fundamental processes built into the model. The complexity of agent-based modeling should be in the results of the model and not in its assumptions.

Aspen-EE was written in C++ to run on single-processor and parallel-processor machines. The scenarios discussed in this report were run with the single-processor version of the model. The parallel-processor version of Aspen-EE, which runs much faster, can be used for large-scale problems.

Our detailed description of Aspen-EE begins with an overview of model agents and the environment in which these agents interact. Next, we point out the major differences between Aspen and Aspen-EE. The discussion then addresses the mechanics of the model and identifies the input requirements. Following are details about the rules of behavior for each agent in the model. The section concludes with a detailed discussion of how the electric power markets in Aspen-EE work.

Overview of Aspen-EE Agents and Their Environment

Agents are the building blocks of Aspen-EE. In its initial implementation, the model contains 10 types (or classes) of agents: household, commercial, industry, government, generation company, independent system operator, fuel company, disaster, bulletin board and weather. The actions of individual agents within these classes are described briefly below.

- A *household agent* works or collects unemployment for income and pays taxes. A household agent spends income on two types of consumer items (produced by commercial and industry agents) and is a user of electric power.

- A *commercial agent* produces mostly perishable goods, employs household agents, pays taxes, and is a user of electric power.

- An *industry agent* produces durable goods, employs household agents, and is a user of electric power.

- A *government agent* collects income, sales, and payroll taxes. This agent also runs a public sector and pays unemployment benefits. The government agent is a user of electric power.

- A *generation company agent* buys fuel from a fuel company agent, and sells electric power to all agents who are consumers of it, i.e., industry, commercial, household, fuel company, and government.

- An *independent system operator agent* accepts bids from the buyers and sellers of electric power and determines the daily market-clearing price of power.

- A *fuel company agent* produces fuel for generation company agents, employs household agents, pays taxes, and is a user of electric power.

- A *disaster agent* informs other agents when a scheduled power outage begins and ends.

- A *bulletin board agent* is a vehicle through which certain agents communicate with each other.

- A *weather agent* determines the daily demand for electric power and posts the demand on the bulletin board.

Figure 1 illustrates the logical relationships between these various agent classes.

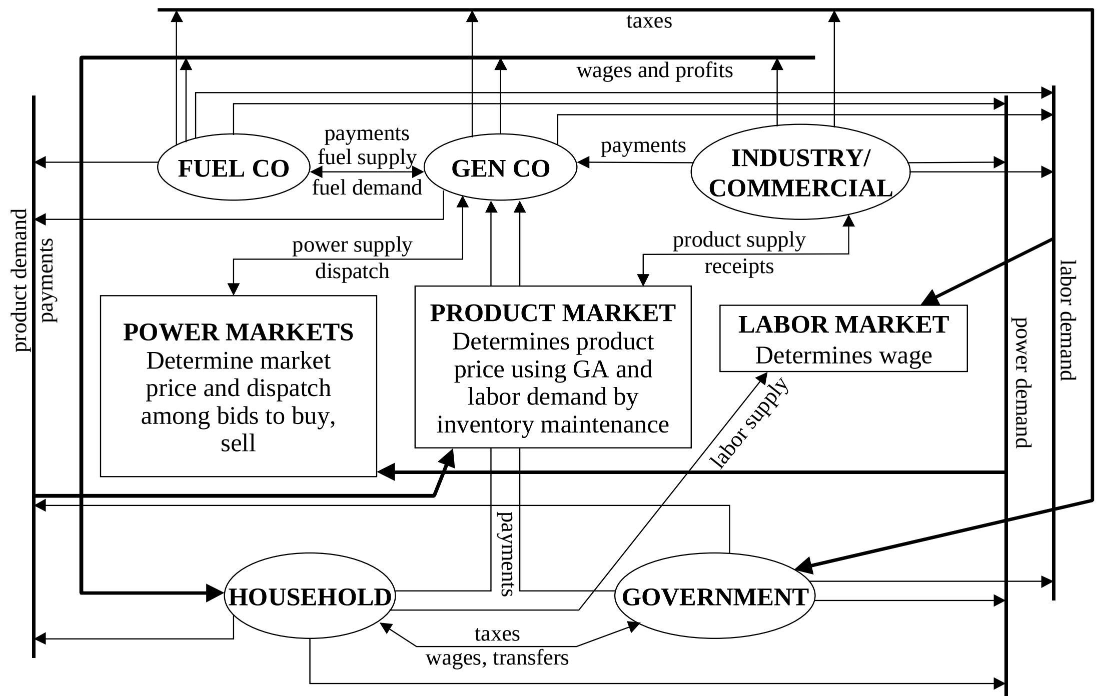

Figure 1. Agent interactions in Aspen-EE.

As shown in Figure 1, there are three kinds of markets in the model. The product and labor markets are also parts of Aspen and thus have been well studied; these markets have demonstrated the potential for better predicting the impact of new economic programs and policies, such as the effects of legal or policy changes of the Federal Reserve on interest rates. The electric power markets, on the other hand, are unique to Aspen-EE. In this initial implementation of the model, these short-term markets conduct transactions once per day, with generation company agents constituting the sellers of power and industry agents the buyers of power. An independent system operator, not shown in the figure, coordinates the buying and selling activities and calculates the price and quantity of power that will be bought and sold in each of the power markets modeled.

Aspen-EE agents and markets are subject to external conditions like power outages and to internal decisions within markets, such as price caps that can be instituted within the power markets to control the cost of electricity.

How Aspen-EE Differs from Aspen

While Aspen-EE is built upon the Aspen model, Aspen-EE differs in several important respects. First, as shown in Table 1, Aspen-EE uses some of the agents in

Aspen and also contains a number of agents that are not currently implemented in Aspen. Second, all of the agents in Aspen-EE have behavior related to electric power—a feature that is not considered in Aspen. The most important new agents in Aspen-EE represent the producers of electricity (generation companies), the market structures that control the production of electricity (independent system operators), and a supplier of electric utility requirements (fuel company) in a restructured environment. Third, Aspen-EE is written in C++, whereas Aspen is a C application. And finally, Aspen-EE employs an event-driven approach to message passing (i.e., communication between agents) to drive the simulation forward, while Aspen follows a time-sequencing approach. See **Mechanics of the Model** for a discussion of Aspen-EE Events.

Table 1. Agent Usage in Aspen and Aspen-EE

Agent Class (Type)	Used in Aspen	Used in Aspen EE	Additional Notes on Aspen-EE Agents
Household	X	X	Modified in Aspen-EE to include electric power behavior
Firm	X		Not used specifically in Aspen-EE: instead differentiated as two classes of agents in Aspen-EE
Bank	X		
Government	X	X	Modified in Aspen-EE to include electric power behavior
Financial Market	X		
Federal Reserve	X		
Realtor and Capital Goods Producer	X		
Commercial		X	Agent based on a type of Firm agent in Aspen
Industry		X	Agent based on a type of Firm agent in Aspen
Fuel Company		X	Agent has similar behavior to a type of Firm agent in Aspen, but this class of Aspen-EE agent is not present in Aspen
Generation Company		X	
Independent System Operator		X	
Disaster		X	
Bulletin Board		X	
Weather		X	

As might also be observed from the agent list in Table 1 above, the representation of the economy in Aspen-EE is more simplified than that found in Aspen. Importantly, however, Aspen agents can be easily modified and used in Aspen-EE for user problems in which the banking system, for example, is of interest. For a description of agents in their original form and agents not used in Aspen-EE, see *Aspen: A Microsimulation Model of the Economy* [9].

The Mechanics of Aspen-EE

Agents in Aspen-EE are decision makers. Each agent behaves the way its counterpart in the real world would behave, as the simulation traces the agent's daily actions (buying goods, hiring workers, collecting welfare payments, conducting open market operations, etc.). Agents in the same class draw from the same decision rules. For example, all individual household agents will use the same rule to decide from which agent that they will purchase product. However, the decision from which agent to actually purchase a product may vary from household agent to household agent because of its own constraints, such as insufficient income to purchase the product desired at a particular point in the simulation or because each household agent uses a different random number in choosing a supplier.

As noted in Table 1, there are 10 classes of agents. The number of individual agents of each type created during a simulation is input by the user. For example, a simulation might contain 450 individual household agents. The current implementation of Aspen-EE organizes the agent classes into two groups, depending on how individual agents of the classes are treated. The first group contains those classes for which there will be many agents (or at least more than one) representing them in a calculation. These classes are household, commercial, industry, generation company, fuel company, and independent system operator. The second group of classes has only a single agent representing them in a calculation. These classes are government, disaster, bulletin board, and weather.

Aspen-EE employs Message Passing Interface (MPI), which is a portable standard for interprocess communications that is specifically designed for robust communications on multiprocessor computers. Consequently, in this discussion, we refer to each "parallel node" as a process—a term that is more appropriate because MPI may schedule more than one process on each processor.

A simulation in Aspen-EE is a sequence of "Events". Fundamentally, an Event is just a point in the sequence where something "interesting" happens. Therefore, an Event is not an "action" – it's more like a piece of paper from a "take-a-number" paper dispenser that one might find at the Motor Vehicle Division (MVD). That is, an Event gives a priority to an abstract concept so that it can be sorted and scheduled. To use the MVD example, your business (which is perhaps a driver's license renewal) is an abstract concept that can be sorted and ordered simply by giving you a piece of paper with a number on it. The order in which MVD customers are processed is then given by an ascending sequence (1, 2, 3…). That is to say, as a customer, you have been given a numerical priority that is independent of your business and one that roughly corresponds to the order in which you arrived at the MVD office (that is, it's a "fair" priority for the particular situation).

In Aspen-EE, the prioritization scheme is a bit more complicated (i.e., we also prioritize by your "business" – Tasks have higher priority than Messages), but the concept is the same. The simulation is accomplished by processing the Events in a correct sequence. There are several types of Events; all have important roles in producing the final output of the model. However, two kinds of Events do most of the work – Task Events and Message Events.

To progress through the simulation, Aspen-EE uses event passing (versus message passing as used in Aspen*)*. There are two types of Events that involve model computations: *task events* and *message events*. Checking one's product supply and paying taxes are examples of task events. Message events encompass communications between agents and cause agents to perform actions based on the content of the message. For example, a commercial agent will send a message to the government agent when it pays taxes. The government agent in turn will read the incoming message and credit the commercial agent's tax payment of the specified amount.

Task events are those Events where Agents independently begin a new sequence of Actions (i.e., time to pay taxes). Message events are those Events where Agents communicate with other Agents, possibly to complete a sequence of Actions. (i.e, a taxpayer debits its account and sends the message "Government, here are my taxes in the amount of $X", with the result of the Government crediting its accounts with that amount).

Aspen-EE uses the notion of a calendar to correctly sequence Events during a simulation. Events are scheduled on the calendar (a priority queue), with different kinds of priorities assigned to the different types of Events. Priority is determined by the Event's time, its type, and any secondary priority determined by the user. At the top of the calendar, which changes dynamically, is always the next possible event—the one with the highest priority.

Conceptually, there is only one calendar; but because communications overhead make it impractical for the calendar to be centralized, we instead distribute "the" calendar among all processes. That is, each process has its own calendar with Events that involve agents belonging to that process. During a simulation, the current priority of the calendar (i.e., the priority of Events each process should execute) is determined by a collective operation that finds the priority of the highest-priority Event(s) on the calendar. Then all processes execute Events with that priority from their local calendars. While Events are being processed, new Events may be scheduled (e.g., message events that occur when an agent sends a message). Those newly scheduled Events are routed to either a transfer queue or the local calendar depending on their destination. Once each process has completed processing all local Events that have the current priority, the transfer queues are exchanged and the Events are scheduled into the correct local calendars. The process repeats until the current priority indicates the current time is beyond the scheduled stop time.

Time in Aspen-EE is divided into a minimum timestep that is determined by the user. Thus one time step can be set to be equivalent to one hour, and any other unit of time can be derived from that. For example if the minimum time step were one hour a day would take 24 timesteps and a week would take168 timesteps, etc. Each time step can have zero or more Events. Since Events are prioritized by time, type, and secondary priority, one can interpret the priority scheme as "dividing" the time step into stages. For example, all task events have higher priority than any message event, and hence all task events will be processed before the first message event. Therefore, we can call the period when task events are being processed, "The Task Stage." Thus, the priority scheme implicitly replicates the Aspen's time-step "stages," but with some added capabilities.

Aspen-EE performs interprocess (or “Cross-Node”) communications using the MPI Library in three distinct “phases”: when preparing the model for parallel execution, when performing the simulation, and when preparing the various output files. The various output files are discussed in the **Aspen-EE Input and Output** section. When preparing the Model for parallel execution, Aspen-EE requires communication to distribute (relocate) Agents from the root process to the other processes, along with any Events associated with the relocated Agents.

When performing the simulation, Aspen-EE requires communication on each shift in priority. Specifically, on each shift, Aspen-EE must determine the new priority and exhange any enqueued Events placed in the transfer queues. Both activities (determining the new priority and exchanging queues) are combined into a single MPI message intended for the target process. Thus, on every shift in priority, each process prepares a MPI message for every other process, then sends and receives the corresponding MPI messages to and from those processes. The sends and receives are layered to avoid deadlock and to ensure all processes can be communicating at any given time.

Further, when performing the simulation, Aspen-EE requires additional communications (at user-specified intervals) to construct the Snapshot File, which is one of the various output files. The additional communications consists of an MPI “Scan” operation to determine file offsets for each process, along with MPI-implementation dependent communications necessary to perform writes to the file (which may occur in parallel).

At the conclusion of the simulation, Aspen-EE requires some minor communications to clean up and finalize some of the output files. Aspen-EE incurs some additional overhead associated with storing and recovering objects in a text format using a portable object-storage and recovery scheme. The objects are stored into “streams” using the object-storage system, and it is those streams that are exchanged on shifts in priority. This text conversion overhead can be reduced by relying on a binary object storage and recovery scheme. At present, the object-storage system is designed to prepare files that are portable, rather than object streams optimized for exchanges between parallel processes.

Aspen-EE Input and Output

The model uses a single user-prepared text file as input and produces several output files. General characteristics of these files are discussed below.

Input File

The Aspen-EE Input File provides initial values for a number of parameters needed during the simulation. A few of these parameters are used for the problem specification, while the majority of parameters define characteristics of the agents (in the different agent classes) that will be created for simulating the problem. Examples of problem-specification parameters are the number of time steps in the problem, the number of individual agents per agent class, and comments about the run.

Initial values for characteristics of the agent classes are required because many of the decisions in Aspen-EE depend on the current state of those characteristics in specific individual agents. For example, a household agent's consumption decisions depend on factors such as family size, savings balance, and current income. Therefore, at the beginning of a simulation, each household agent is assigned (among other things) an amount of starting cash (savings) and a composition (a number of adults and a number of children). Initial values for these kinds of parameters are typically specified by the user as a constant value (e.g., savings = 1000) or as a range of values from which a single value is chosen (e.g., savings = 1000–5000). When expressed as a range, chosen values for all the household agents are uniformly, randomly, distributed over that range. By using this approach, Aspen-EE can usually create agents that are "different" enough to represent a heterogeneous population. Sometimes, however, this approach will not generate a satisfactory distribution, and an actual distribution can be specified instead. For example, Aspen-EE specifies an actual distribution for the household agent compositions such that single adult households are much more common than 4-adult-2-child households—a condition that would otherwise be equally probable with our randomized parameters. To accommodate the specification of actual distributions and other kinds of ordered data, Aspen-EE also accepts an *array* of initial values for certain input parameters. The capability to specify arrays as a method of parameter initialization is new to Aspen-EE, as no previous version of Aspen features this capability.

During a simulation, the initial values assigned to some of the parameters in the input file can and do change. For example, the amount of savings assigned to a household agent will change from its initial value as the agent spends money, works, and if not working, receives unemployment. On the other hand, certain initial values do not change. Household compositions, for example, are fixed during a simulation.

Appendix A defines the parameters in the input file and provides examples of initial values assigned to these parameters. Note that if the user does not enter an initial value for a parameter, a default value is used and the user is warned to that effect.

Output Files

Aspen-EE produces a primary data file, called the Snapshot File, and derives from it several auxiliary files. The Snapshot File contains a subset of the model's state at periodic intervals – notably the state or values of interesting parameters like the household agents' savings balances. Because the Snapshot File is large and its format is not convenient for plotting, it is subsequently processed by a utility that creates Report Files. These Report Files are then imported into programs such as Microsoft Excel™ or Matlab™ to produce graphic output like that shown in the **Results and Analysis** section of this document.

Aspen-EE Agent Rules of Behavior

This subsection reviews the decision rules for agents from each of the different classes.

Household Agent Rules

Most agents in Aspen-EE are households. Each household is effectively treated as a single entity, though the household is composed of some number of members. Household agents generate all of their income through employment, working to buy widgets and electricity to maximize utility and/or satisfaction. The employers of household agents are commercial, industry, government, generation company, and fuel company agents.

The household agent obtains a job by accepting a job offer message and is paid a salary by the employer until the household agent/employee quits or is fired. If at any time a household agent is not employed, this agent collects an unemployment benefit from the government agent, with the amount of payment dependent on family size. All household agents pay a flat-rate income tax.

Household agents consume two kinds of goods each day: commercial and industrial. For the purposes of the model we assume that commercial goods, like food, decay during a power outage, whereas industrial goods are not affected by power outages. A household agent's goods consumption is not determined in the usual way, i.e., there is no exogenous utility function that is maximized over all feasible consumption bundles. Rather, Aspen-EE uses simulation techniques and reasonable rules of thumb.

Demand for commercial and industrial goods is assessed daily based on family size. When this demand has been determined, the household agent identifies a suitable commercial or industry agent. The household agent first consults a list of per-unit product prices that are broadcast daily by commercial and industry agents and uses the following logic to determine what product to purchase.

For example, if a commercial or industry agent (assume one named "commercial *f*") offers food for price p(*f*), the household agent buys this food from commercial *f* with a probability $k*[p(f)]^{-q}$

where q = a given exogenous parameter defined by the user, and
k = a normalizing constant.

Thus, the lower $p(f)$ is in relation to other commercial or industry agents' prices, the greater chance the household has of satisfying its demand by buying from commercial *f*.

Household agents are daily consumers of electricity, with the amount of usage specified by the user. When there is a power outage, household agents' need for industry and commercial products is reduced, also by a user-specified amount. Household agents do not bid into the electric power market. Instead, they consult the bulletin board, where the generation companies post the daily price for their customers in the firm market—the group to which household agents belong. See **Generation Company Agent Rules** for a discussion of firm and nonfirm markets.

Household agents begin the simulation with an initial cash reserve, as specified by the user. During the simulation, this amount increases when an agent has income and decreases when an agent purchases products and electricity and when an agent pays taxes. The household agent keeps track of its cash on hand as the simulation progresses. In the current implementation of Aspen-EE, banks are not represented. Thus household agents do not earn interest on their cash balance.

Commercial, Industry, and Fuel Company Agent Rules

Aspen-EE has three classes of agents that represent business groupings in the economy: commercial, industry, and fuel company. All three classes of agents produce goods and sell their goods, employ household agents, and use electric power. And these agent classes share many of the same decision rules, varying mostly in the kinds of goods they produce and their behavior related to obtaining electricity. For these reasons, we have chosen to discuss the commercial, industry, and fuel-company agent classes together and to highlight differences where applicable.

Goods Production

Commercial agents produce perishable goods, industry agents produce nonperishable goods, and fuel company agents produce fuel, specifically natural gas. These agents all use capital and labor to produce their goods and have production functions of the form $y = c\,K^{a} L^{b}$

where y = output of goods on a given day,

K = *number of machines on hand in the factory, and*
L = number of employees.

The quantities a, b, and c in the above equation are constants, with the value of c the same for each of the three agent classes. Commercial, industry, and fuel company agents currently can only vary production by adjusting L, the number of its employees.

Product Sales and Prices

Commercial and industry agents sell their products to household agents; fuel company agents only sell their product (fuel) to generation company agents. To simulate how the commercial, industry, and fuel company agents set prices for their products, Aspen-EE uses a genetic algorithm learning classifier system (GALCS) in which the agents determine four trends daily: (a) whether the product price has been recently increasing or decreasing, (b) whether sales have been recently increasing or decreasing, (c) whether profits have been recently increasing or decreasing, and (d) whether prices are higher or lower than the industry average. Based on answers to (a) through (d), the agent finds itself in one of 16 states.

The GALCS assigns a probability vector (p^D, p^I, p^C) to each state

where p^D = probability that the agent will decrease a given price (by a certain exogenously specified amount) the next time the agent enters the same state,
p^I = probability that the agent will increase the price, and
p^C = probability that the agent will keep the price constant.

Upon entering a certain state, the commercial, industry, or fuel company agent decides how to change a given price by using the corresponding probability vector and choosing a random number. The agent then adjusts the vector according to how the price change affects profits. The example below can help to explain this process.

Suppose that at a particular time for state 2, the following condition exists: (p^D, p^I, p^C) = (.1, .6, .3). Assume that a commercial agent then enters this state and draws a random number indicating the need for a price increase. Suppose further that as a result of increasing the price, profits drop. To reflect this drop, the vector is then adjusted to (.15, .5, .35). Thus, Aspen-EE simulates the agent's learning process. The agent learns that raising prices in state 2 was detrimental. As a result of an incorrect decision, the vector is adjusted to reflect a decreased probability of a price increase. The changed probability vector reflects the unlikelihood that the agent will increase prices upon re-entry into state 2.

For more details on GALCSs and GALCS results from other Sandia runs, see *Aspen: A Microsimulation Model of the Economy* [1].

Taxes

Commercial, industry, and fuel company agents must pay taxes on their profits.

Employment of Workers

Each day a commercial, industry, and fuel company agent can hire or fire workers. This decision results from comparing recent average daily demand with the current inventory level. If the quantity (inventory minus demand) is less than a certain constant, the agent issues job offers; if inventory minus demand is greater than a certain other constant, the agent issues pink slips. Wages paid to household agents are constant for a particular hiring agent (i.e., commercial, industry, or fuel company agent). Workers do look for jobs that pay more. If a worker finds a job, there is a probability (nearly but not equal to 100%) that the worker will take the job. The less than 100% probability of taking a higher paying job reflects factors such as job loyalty, difficulties in starting a new job, etc.

Electric Power Consumption and Purchasing

Commercial, industry, and fuel company agents all use electricity to produce their products and purchase the power from a generation company agent. How the power is purchased, however, is dependent on the agent's class. Commercial and fuel company agents purchase electricity as "firm" customers, where they are charged a fixed amount for power used. Industry agents, on the other hand, purchase electricity as "nonfirm" customers, where they bid for electricity in an electric power market and are subject to the varying possible costs from day to day. See **How Industry Agents Bid in an Electric Power Market** below for further details.

Impact of Power Outages

As consumers of electricity, commercial, industry, and fuel company agents are all affected by power outages. Commercial agents are affected the most, however. During a power outage, commercial agents, which produce perishable goods (e.g., ice cream), can experience a reduction in inventory, productivity, and power. The loss in inventory and productivity is specified by the user via input parameters to the model. The inventory loss continues after the power outage is over; worker productivity is only reduced during the outage. Regarding the loss in power, commercial agents have no power (or a lower percentage) during the course of the outage and return to their normal power consumption after the outage. In some cases, commercial agents may have to increase their power consumption later in the simulation to boost their inventory to previous levels.

Industry and fuel company agents experience reductions in productivity during a power outage in the same fashion as described above for commercial agents. However, neither industry nor fuel company agents suffer from a loss in inventory during an outage (or thereafter). Like commercial agents, industry and fuel company agents have no power during an outage and return to their normal consumption after the outage.

How Industry Agents Bid in an Electric Power Market

During a simulation, an industry agent submits a daily bid for electricity into one electric power market—the market that services the region in which the industry agent is located. Any number of industry agents, as defined by the user, can bid into a single power market. The goal of industry agents in a power market is to pay less for electricity, and thus maximize their profit.

Each industry agent has a certain demand for power that is dependent on factors such as its size, the weather, and previous profits. Via specific input parameters, users can tailor individual industry agents to resemble different-sized industries that pay different amounts for power based on their size.

Each bid submitted by an industry agent consists of a price and a quantity for a specific period of time, $P(t)$ and $Q(t)$. The ISO that processes that bid returns back a price $P^*(t)$ that the agent will pay to satisfy that quantity $Q^*(t)$. The industry agent is guaranteed that the quantity will be met because this is a market of last resort.

The **process** by which an industry agent determines the price and quantity for power for time t (or daily) that it will bid is described below in two parts (A and B), which occur sequentially. This process is based on startup parameters in the Aspen-EE Input File, where each agent i is assigned an initial value for mean quantity ($Qbar_i$) in megawatts (MW) when $D(t) = 1$, for mean price ($Pbar_i$) at the mean quantity, and for a price gradient ($\nabla P_i(0)$). Below are some initial values assigned to these parameters for three industry agents, such that, for example, the mean price per unit of power for industry 1 is 65 dollars and this agent has a demand for a mean quantity of 40 units. The price gradient for this agent is 0 because no previous bid has been calculated and a gradient is essentially a comparative value between prices.

Number$_I$ i	**Mean Quantity $Qbar_i$ in MW**	**Mean Price $Pbar_i$ in dollars per MW**	**Price Gradient $\nabla P_i(0)$**
1	40	65	0
2	15	74	0
3	5	83	0

To illustrate the bidding process, we will use the initial values for industry 1 and provide an example of how this agent determines the price and quantity values in a bid.

Part A: Determine Quantity for Bid

The industry agent determines the quantity that it will bid for time t, $Q(t)$. The value of $Q(t)$ is the product of the demand multiplier $D(t)$, which is computed by the weather agent and posted on the bulletin board, and the value of $Qbar_i$, the mean quantity:

$$Q(t) = D(t) * Qbar_i. \quad [1]$$

Thus, for example, if we are computing $Q(t)$ for industry 1 and assume a value of $D(t) =$ 1.1 (10 percent above normal), then we determine that the quantity the agent will demand in the bid is 44 MW, as $Q(t) = 1.1 * 40 = 44$.

Part B: Determine Price for Bid

The industry agent next calculates the price that will be associated with the quantity computed in Part A above. The price calculation consists of three steps.

1. The industry agent determines the price multiplier for time t, expressed as *MP(t)*. The value of *MP(t)* is obtained by querying a price multiplier matrix defined by the user for the particular industry agent. This matrix is constructed based on the value of *D(t)*, as obtained for the associated quantity bid, such that for any value of *D(t)* there is an associated price multiplier.

   For our example, assume the following for industry 1:

D(t)	.9	1	1.1	1.2	1.3
MP(t)	–0.3	0	0.1	0.9	9.0

   Thus, when *D(t)* = 1.1, the value of *MP(t)* = 0.1.

2. Next, the industry agent computes the price gradient for the current time, referred to as $\nabla P_i(t)$. This calculation consists of two substeps, as follows:

   a) First, the agent computes the Difference Percentage, referred to as *D%*, which is the difference between the price the agent paid for power at the previous bidding time, referred to as *P*(t-1)*, to the price the agent bid for power at this previous bidding time, i.e., *P(t-1)*, relative to the maximum of these two values. A positive percentage means that the industry agent paid more for the power than it bid; a negative percentage means that the industry paid less than it bid. Thus,

   $$D\% = [P^*(t-1) - P(t-1)] \,/\, \mathrm{Max}\,\{P^*(t-1), P(t-1)\}. \qquad [2]$$

   For our example, assume that industry 1 paid 64 dollars per unit of power at the previous bidding time but bid 90 dollars per unit of power. Then *P*(t-1)* = 64 and *P(t-1)* = 90, then *D%* = (64 – 90) / 90 = -0.29. Thus industry 1 bid more than it paid.

   b) Next, the agent needs to adjust its position relative to the market and thus recomputes the gradient as follows:

      - If the price bid at the previous time, *P(t-1)*, is less than the price paid by the industry agent at that previous time, *P*(t-1)*, then the value of the gradient $\nabla P_i(t)$ is equal to the value of the gradient for the previous time, $\nabla P_i(t-1)$ plus one-fifth of the computed difference percentage *D%*. This logic is stated as

        If $P(t-1) < P^*(t-1)$ then $\nabla P_i(t) = \nabla P_i(t-1) + D\% / 5$.

- If the price bid at the previous time, *P(t-1)*, is greater than or equal to the price paid by the industry agent at that previous time, *P*(t-1)*, then the value of the gradient $\nabla P_i(t)$ is equal to the value of the gradient for the previous time, $\nabla P_i(t-1)$ plus one-half of the computed difference percentage *D%*. This logic is stated as

  If $P(t-1) \geq P^*(t-1)$ then $\nabla P_i(t) = \nabla P_i(t-1) + D\% / 2$.

  Thus, for our example, where D% for industry 1 = -0.40 (a negative value), then $\nabla P_i(t) = 0.0 + (-0.29)/2 = -0.14$.

3. Finally, the industry agent determines the price of the bid at time t, referred to as *P(t)*, given the initial mean price ($Pbar_i$), the price multiplier *MP(t)* calculated in step 1 of Part B, and the adjusted gradient $\nabla P_i(t)$ calculated in step 2 of Part B:

   $$P(t) = Pbar_i * [1 + (MP(t) + \nabla P_i(t))]. \qquad [3]$$

   So, for our example,

   $P(t) = 65 * [1 + (0.1 + ((-0.14))]$
   $= 65 * [1 + (-0.04)]$
   $= 62.1.$

   Thus industry 1 will submit a price bid of \$62.1/MWfor a quantity of 44 MW (as calculated in Part A above).

Government Agent Rules

Each month the Aspen-EE government agent collects taxes from all other agents based on a user-specified tax rate. The government agent also pays a daily benefit to the unemployed, which it keeps track of via a list that household agents enter and leave based on their employment status. In the current implementation of the model, the government agent has no employees, but the capability exists that would allow this agent to hire, fire, and pay employees. Like several of the other agents in the model, the government agent consumes electricity, pays its power bill monthly, and is affected by a power outage. During a power outage, the government agent uses no power and, in the case of a scheduled power outage, its cash assets are reduced by a user-specified amount. Once the outage is over, this cash loss is not restored, resulting in a permanent loss in assets for this agent.

Generation Company Agent Rules

The generation company agents, referred to herein as GenCos, are players in Aspen-EE's electric power markets. The actions of these agents consist of buying fuel from the fuel company, buying supplies from industry, hiring and firing employees, and selling power via bidding into the power markets. Described below are the rules that govern and affect the behavior of GenCos.

Purchase of Fuel

All GenCos in a particular power market purchase fuel from the same fuel company agent and use this fuel to produce power, based on power demand and generating capacity. When the fuel supply falls below the desired fuel amount (an input parameter specified by the user), a GenCo purchases more fuel, obtaining the price of the fuel from the bulletin board. The amount requested by a GenCo is equal to the difference between the desired fuel amount and the current fuel supply. This amount is increased by a desired fuel excess amount, which is another input parameter, and becomes the amount of fuel ordered, which is sent in the form of a purchase request to the fuel company agent. Upon receipt of a purchase request, the fuel company agent notifies the GenCo the amount of the order it was able to fill. The fuel company agent always fills the full request unless it doesn't have the inventory to cover the order. If the fuel company falls short in the order, it will sell its full inventory and notify the GenCo that it could not fill the entire order.

Purchase of Other Supplies

A GenCo purchases supplies in much the same way it purchases fuel. Supplies are needed to keep the generators running and are purchased from industry. The needed supplies are determined by subtracting the desired supplies (an input parameter provided by the user) from the actual supplies. If the resulting value is a positive number, the desired excess supplies (another user-provided input parameter) is added to the value, becoming the amount that is ordered from industry.

A GenCo obtains the price of supplies from the bulletin board where industry posts its price. The GenCo then orders supplies based on the best price it can find from industry. There is a small probability that the GenCo will not order from the low-cost provider to reflect loyalty to a specific supplier. If a GenCo cannot get its full order filled, the agent will re-order at the next time step until it has more supplies than the desired supply amount.

Employment of Workers

The GenCos have the capability of hiring workers, but currently this capability is not being used. A GenCo's ability to generate electricity is based on its current fuel supplies rather than on employees. Industry, commercial, and fuel company agents all use employees as a means of being able to produce inventory. A GenCo could use both fuel and employees, but it currently uses just fuel. If GenCos ever do hire employees, they will do so in much the same way that industry agents hire workers.

Taxes

GenCos must pay taxes on their profits. A GenCo performs this action with a PayTaxTask that is exactly the same as that used by industry agents. A GenCo's tax rate is specified by the user in the input file. The GenCo calculates its taxes as a percentage of the profits determined by the tax rate. It then pays its taxes to the government and resets its tax bill to zero. Taxes are paid monthly. However, it should be noted that the current version of Aspen-EE does not include the payment of taxes by GenCos, nor is there any tax rate specified in the input file for GenCos. Future versions of Aspen-EE are likely to have this taxpaying feature.

Electric Power Consumption and Sales

Although GenCos sell power, they are not treated as consumers of electricity in the current version of Aspen-EE. GenCos sell power to two types of customers: firm and nonfirm. Firm customers are those for whom the GenCos provide a "firm" commitment to serve. In the current implementation of Aspen-EE, these customers pay a standard negotiated (fixed) rate for the length of the simulation—a rate that is specified for each GenCo by the user; nonfirm customers must bid for power that will be supplied by GenCos. Firm customers are households, government, commercial, and fuel company agents. Only industry agents are nonfirm customers. However, this can be changed fairly easily to reflect a larger (or smaller) number of nonfirm customers.

A GenCo gives its firm customers priority over its nonfirm customers when satisfying demand for power. If a GenCo cannot meet the demand of its firm customers during a time step, the company communicates this information to these customers and effectively initiates a fuel-induced power outage. If a GenCo has excess power to meet the demand of its firm customers, the company will bid this excess demand in one or more electric power markets. See **How GenCos Bid into Electric Power Markets** below.

Periodically, GenCos bill their customers for the amount of power used during the specified period. Both firm and nonfirm customers pay their GenCo directly for power used approximately once per month.

Impact of Power Outages

GenCos are indirectly affected by power outages (both scheduled and unscheduled). For example, their demand is reduced, which may affect decisions on production and amount of fuel ordered. When a scheduled power outage occurs, a GenCo notifies its customers. When an unscheduled power outage occurs (e.g. insufficient fuel), the affected GenCo attempts to buy power from other GenCos. If there still is less power than is needed to supply its own customers, the ailing GenCo will start notifying its customers of an outage in the same way it does for a scheduled outage. To the end-users, there is no difference between a scheduled and an unscheduled power outage.

Impact of Price Caps

GenCos must respect the rules of any electric power market into which they bid. If the ISO of any market has implemented a price cap on that market, GenCos cannot receive prices higher than the cap and should not place bids into that market for prices higher than the cap; otherwise, the ISO will reject the bid outright. If the ISO does not have a price cap, then the GenCos are free to bid as high as they wish into that market.

How GenCos Bid into Electric Power Markets

During a simulation, a GenCo can submit a daily bid into one or more electric power markets. The goal of GenCos in power markets is to obtain a higher price for their power, and thus increase their market share. While a GenCo wants to increase its price for power, the GenCo does not want to increase that price to the point where another GenCo will outbid it at a lower price and steal its market share.

Each bid submitted by a GenCo consists of a price and a quantity for a specific period of time, $P(t)$ and $Q(t)$. The ISO that processes that bid returns back a price $P^*(t)$ that the agent will get paid to produce a given quantity $Q^*(t)$. There is no guarantee that a GenCo will sell all the quantity it offered in a bid.

The **process** by which a GenCo determines the price and quantity of power for time t (or daily) that it will bid into one or more markets is described below in three parts (A, B, and C), which occur sequentially. This process is initially based on a startup parameter in the Aspen-EE Input File, where each GenCo is assigned a total generation capacity for time t, $q_T(t)$, which is a specified quantity that does not change during the simulation unless there is a loss in this capacity due to a power outage. Below is an initial value assigned for a particular GenCo, such that, for example, the total generation capacity for GenCo 1 is 600 megawatts (MW).

Name	**Total Capacity in MW**
GenCo 1	600

To illustrate the bidding process, we will use this initial value for GenCo 1 and provide an example of how this agent determines the price and quantity of bids.

Part A: Determine Nonfirm Quantity Available for Bidding into Market(s)

Per Equation 1 below, the value of $q_T(t)$, the total generation capacity at time t for a GenCo, is equivalent to the sum of the quantity that the agent bids for its firm customers at time t, $q_F(t)$, and the quantity that it bids for its nonfirm customers at time t, $q_{NF}(t)$.

$$q_T(t) = q_F(t) + q_{NF}(t) \qquad [4]$$

Thus, based on Equation 4 the GenCo (who knows its total capacity) determines the nonfirm quantity available for bidding into the market(s) as follows:

1. The GenCo first calculates its firm quantity, $q_F(t)$, which represents the amount of power it must reserve for its firm customers. Per equation 5 $q_F(t)$ is the product of the demand multiplier $D(t)$, which is computed by the weather agent and posted on the bulletin board, and the value of the mean firm quantity, q_F*.

   $$q_F(t) = [\ D(t)]\ [\ q_F*\ ] \qquad [5]$$

   NOTE: The value of q_F* is actually the product of two values: the static usage (or power demand per firm customer) and the total number of individual firm customers served by the GenCo. The static usage is an input parameter. Part of the GenCo's knowledge during the simulation is how many of these input customers it serves.

   So, for our example, assume a value of $D(t)$ = 1.1 (10 percent above normal) and also assume that GenCo 1 serves 400 customers and has a static usage of 1 MW per customer. Thus, $q_F(t)$ for GenCo 1 is 440 MW, as $q_F(t)$ = 1.1 * (1 * 400) = 440 MW.

2. The GenCo then uses Equation 6 (an alternate form of Equation 1) to calculate the nonfirm quantity, $q_{NF}(t)$. The value computed in step 1 is subtracted from the given generation capacity as

   $$q_{NF}(t) = q_T(t) - q_F(t) \qquad [6]$$

   So, based on Equation 6, $q_{NF}(t)$, the total quantity that GenCo 1 can bid into the market(s), is 160 MW, as 160 = 600 – 440.

Part B: Determine Quantity of Bid

Next, the GenCo needs to determine how to divide its non-firm quantity (computed in part A) for bidding into the available markets. The rule set for bidding depends upon how many markets there are in the scenario. If there is only one market, a GenCo will bid its available quantity at a varying price into that one market. Where two or more markets are involved, however, the GenCo must be concerned with both price and quantity issues. Thus in the single-market case, price varies but quantity bid into the market does not. In the multiple-market cases, a GenCo has to determine both the price and quantity it will bid into each market.

<u>Special rules for multiple markets</u>:

- For initialization purposes, each GenCo will divide its available nonfirm quantity in equal portions among the markets.

- A GenCo cannot bid more than 3/4 of its nonfirm quantity in any one market when multiple same-time markets exist.

There are two distinct activities that are required to determine the quantity a GenCo bids into the available markets, as described below in Parts B1 and B2.

B1: Determine the winning market. The GenCo will determine the quantity to bid at the current time step based upon the winning market in the previous bid. The winning market is the one in which the GenCo achieved the highest ratio of total revenue to total cost. If there is only one market, then that market is the winning market and Part B1 is not applicable.

To determine the winning market when there are multiple markets, the GenCo does the following:

1. For each market in which the GenCo participated during the previous bidding time, the GenCo computes a ratio of total revenue to total cost, which is a function of the market clearing quantity ($Q^*(t-1)$), and price ($P^*(t-1)$) determined in the last market-clearing step $t-1$, as well as the marginal operating cost (c_μ) of generation for that GenCo, as expressed in Equation 7:

   $$[P^*(t-1) \; * Q^*(t-1)] \,/\, [c_\mu \; * Q^*(t-1)] \qquad [7]$$

   The value of c_μ is a user input for the particular GenCo.

   For our example, we will assume that in the previous bidding time (but not the first time step in the simulation) that GenCo 1 bid into two markets. The values applicable to Equation 7 are also assumed for GenCo 1, as

	$P^*(t-1)$	$Q^*(t-1)$	c_μ
Market 1	50	60	35
Market 2	60	90	32

   Thus, for our example, using Equation 4, the two ratios calculated for GenCo 1 are

   Market 1 Ratio: (50 * 60) / (35 * 60) = 1.43
   Market 2 Ratio: (60 * 90) / (35 * 90) = 1.71

2. The GenCo then ranks (in descending order) the ratios determined in the previous step. The highest ratio is the winning market.

   So, for our example, Market 2 is the winning market while Market 1 is a losing market.

B2: Determine the quantity to bid in the winning and losing markets. Once the GenCo knows the winning market, it can determine what quantity to bid in that market at the current time step, $q_W(t)$, as well as $q_L(t)$, the quantity to bid in the losing market(s). The value of $q_W(t)$ is the product of the nonfirm quantity $q_{NF}(t)$, as calculated in Part A, step 2 above, and the share of nonfirm quantity bid into the winning market, $s_W(t)$, as given in Equation 8:

$$q_W(t) = q_{NF}(t) * s_W(t). \qquad [8]$$

The share of the nonfirm quantity bid into the winning market is determined using the following procedure:

1. The GenCo must first determine the share of nonfirm quantity bid into the winning market, $s_W(t)$. The value of $s_W(t)$ is equal to the quantity for the GenCo in the same market at the previous time, $s_W(t-1)$, plus a 'gradient of share' ∇s_w, as expressed in Equation 9.

$$s_W(t) = s_W(t-1) + \nabla s_w \qquad [9]$$

∇s_w is a function of the expected and previous demand ($D(t)$ and $D(t-1)$) that were determined by the weather agent, the quantity bid into the winning market ($q_W(t-1)$) and the market clearing quantity in the winning market ($q_W{}^*(t-1)$).

The value of ∇s_w is determined according to the following logic:

- If the quantity that was bid by the GenCo into the winning market, $q_W(t-1)$, is greater than or equal to the market clearing quantity $q_W{}^*(t-1)$, then the value of ∇s_w is determined using state matrix M2 (see Table 2).

Table 2. State Matrix M2 to Determine ∇s_w

M2	*D(t)*					
	From \ to	.9	1	1.1	1.2	1.3
D(t-1)	.9	.01	.01	.02		
	1	.01	.01	.01	.02	
	1.1	.005	.01	.01	.02	.03
	1.2		.005	.01	.02	.03
	1.3			.01	.01	.03

- If the quantity that was bid by the GenCo into the winning market, $q_W(t-1)$, is less than the market clearing quantity $q_W{}^*(t-1)$, then the value of ∇s_w is equal to 0.

For our example, let us assume that the value of *D(t-1)* was 1.0 (normal). And we know already that the value of *D(t)* is 1.1 (10 percent above normal). Let us also assume that the quantity that was bid by the GenCo into the winning market at the previous time, $q_W(t\text{-}1)$, was 100, which is 10 more than the market clearing quantity of 90. Therefore, we use matrix M2 to determine ∇s_w and find that the gradient is equal to .01, which is the intersecting cell when *D(t-1)* = 1 and *D(t)* = 1.1.

2. Given ∇s_w, the GenCo then calculates $s_W(t)$ based on Equation 9 above.

   For our example then,

$$
\begin{aligned}
s_W(t) &= s_W(t-1) + \nabla s_w \\
&= (100/160) + 0.01 \\
&= 0.625 + 0.01 \\
&= 0.635.
\end{aligned}
$$

3. Now, the GenCo can calculate $q_W(t)$, the quantity to bid in the winning market for the current time step. However, one of the rules for multiple markets is applicable in that no more than two-thirds of the total nonfirm quantity (for two markets) can be bid into the winning market.

   The GenCo agent calculates $q_W(t)$ per Equation 8:

$$q_W(t) = q_{NF}(t) * s_W(t).$$

   Thus, for our example, $q_W(t) = 160 * 0.635 = 102$.

   If $q_W(t)$, however, is greater than two-thirds the value of $q_{NF}(t)$, then the GenCo must recompute the value of $q_W(t)$ by equation 10 as

$$q_W(t) = 2/3 * q_{NF}(t). \qquad [10]$$

   Because the value of 102 for our example is less than 2/3 of 160 (or 106.7), then the value of $q_W(t)$ is valid and GenCo 1 will submit a quantity of 102 units of power into Market 2 at time step *t*.

4. Finally, the GenCo can determine the quantity for the 'losing' market, $q_L(t)$, per Equation 11:

$$q_L(t) = q_{NF}(t) - q_W(t). \qquad [11]$$

   For our example, then, GenCo 1 will submit a quantity of 58 units of power into Market 1, the loser, at the current time step (i.e., 160 – 102 = 58). The logic for this case is defined for a circumstance in which there are only two same-time markets for power (the cases examined in the research). An alternate logic will be required to define losing market behavior for those cases in which a GenCo is actively bidding into more than two same-time markets (where naturally there will be more than one 'loser').

Part C. Determine price of bid

The GenCo next needs to determine the price for power in each market *m* at time *t*, $p_m(t)$, for the quantity previously calculated. The price is a function of the marginal cost, c_μ; a demand multiplier, $\rho 1_m(t)$, a market-success adjuster, $\rho 2_m(t)$, and the desired profit margin for the GenCo, M_Π, expressed in Equation 12 as

$$p_m(t) = [\ c_\mu\ ]\ [\ 1 + (\rho 1_m(t))(1+(\rho 2_m(t)/100))(M_\Pi)], \qquad [12]$$

where

c_μ, the marginal cost of generation for the GenCo, is a user-specified input;
M_Π, the desired profit margin for this GenCo is a user-specified input;
$\rho 1_m(t)$, the demand price multiplier for this GenCo in market *m* at time *t*, must be calculated; and
$\rho 2_m(t)$, the market-success adjustment multiplier for this GenCo in market *m* at time *t*, must be calculated.

The price calculation consists of three steps.

1. The GenCo determines the demand price multiplier in market *m* at time t, expressed as $\rho 1_m(t)$. This multiplier is obtained by querying a price multiplier matrix defined by the user for the particular GenCo. This matrix is constructed based on the value of $D(t)$, as obtained for the associated quantity bid, such that for any value of $D(t)$ there is an associated price multiplier. As can be observed in the matrix, with increases in demand above normal (i.e., greater than $D(t) = 1$), the demand price multiplier increases significantly.

   For our example, assume the following for GenCo 1:

$D(t)$	.9	1	1.1	1.2	1.3
$p1_m(t)$	.9	1	1.3	3	30

   Thus, when $D(t) = 1.1$, the value of $\rho 1_m(t) = 1.3$

2. Now, the GenCo must determine the market-success adjustment multiplier in market *m* at time *t*, expressed as $\rho 2_m(t)$. This value is determined according to the value of the market-success adjustment multiplier in the previous bidding time, $\rho 2_m(t\text{-}1)$, and the 'price-demand gradient', ∇p_m, by Equation 13:

$$\rho 2_m(t) = \rho 2_m(t\text{-}1) + \nabla p_m. \qquad [13]$$

   a) The value of ∇p_m is determined according to the following logic:

- If market m is the winning market, then

  - If the quantity that was bid by the GenCo into the winning market at the previous bidding time, $q_m(t-1)$, is greater than or equal to the market clearing quantity $q_m{}^*(t-1)$, then the value of ∇p_m is equal to 0.

  - If the quantity that was bid by the GenCo into the winning market at the previous bidding time, $q_m(t-1)$, is less than the market clearing quantity $q_m{}^*(t-1)$, then the value of ∇p_m is determined using state matrix M3 (see Table 3)..

- If the market is a losing market, then the value of ∇p_m is determined using state matrix M4 (see Table 4).

For our example, the value of $D(t-1)$ is 1.0 (normal) and the value of $D(t)$ is 1.1 (10 percent above normal). We also know that the quantity that was bid by the GenCo into the winning market (market 2) at the previous time, $q_2(t-1)$, was 100, which is 10 more than the market clearing quantity of 90. Therefore, based on the above logic, ∇p_2 is equal to 0. For market 1, ∇p_1 is equal to the cell in Matrix M4 where the value of D(t-1) and the value D(t) intersect, or –1.

Table 3. State Matrix M3 to Determine ∇p_w Given *D(t-1)* and *D(t)*

M3	*D(t)*					
	From \ to	.9	1	1.1	1.2	1.3
D(t-1)	.9	0	0	4		
	1	0	0	3	9	
	1.1	-1	-1	0	5	8
	1.2		-8	-5	0	6
	1.3			-10	-6	-1

Table 4. State Matrix M4 to Determine ∇p_L given *D(t-1)* and *D(t)*

M4	*D(t)*					
	From \ to	.9	1	1.1	1.2	1.3
D(t-1)	.9	-5	-2	1		
	1	-8	-6	-1	1	
	1.1	-10	-10	-8	-1	1
	1.2		-11	-11	.02	-2
	1.3			-15	-9	-5

b) Given ∇p_m the GenCo then calculates the market-success adjustment multiplier $\rho 2_m(t)$ based on Equation 13 above, as

$\rho 2_m(t) = \rho 2_m(t\text{-}1) + \nabla p_m$

For our example, we will assume that $\rho 2_2(t\text{-}1)$ is equal to -1 and ∇p_2 is equal to 0 based on the above determination, Part C, step 2. Thus, for GenCo 1, $\rho 2_2(t)$ is equal to -1 (i.e., -1 + 0). A similar calculation can be performed for the market-success adjustment multiplier for market 1, $\rho 2_1(t)$. If it was known that $\rho 2_1(t\text{-}1)$ were equal to 5, and given the calculation of ∇p_2 as equal to –1, then it could be calculated that $\rho 2_1(t)$ = 5 + (-1) = 4.

3. Now, the GenCo calculates the price to bid in each market m for the current time step by plugging values into Equation 12, repeated below.

$$p_m(t) = [\ c_\mu\ ]\ [\ 1 + (\rho 1_m(t))(1+(\rho 2_m(t)/100))(M_\Pi)],$$

For our example, we will assume a desired profit margin M_Π of 0.2. Prices for each market are calculated as follows:

$$\begin{aligned} p_1(t) &= [\ 32\ ]\ [\ 1 + ((1.3)(1+ ((-4/100))(.2))] \\ &= [\ 32\ ]\ [\ 1 + .27] \\ &= 40.7 \\ p_2(t) &= [\ 32\ ]\ [\ 1 + ((1.3)(1+ ((-1)/100))(.2))] \\ &= [\ 32\ ]\ [\ 1 + .26] \\ &= 40.3 \end{aligned}$$

Thus, GenCo 1 will submit a the following bids at time t:
To market 1, a bid of 58 MW at a price of $40.7/MW, and
To market 2, a bid of 102 MW at a price of $40.3/MW.

Independent System Operator Agent Rules

An ISO (independent system operator) agent coordinates the bidding process in an electric power market. Modeled to represent a real-world entity in the restructuring environment, this agent accepts all bids from generation company agents (sellers) and industry agents (buyers), calculates the market clearing price (MCP) for the day, and notifies the sellers and buyers the quantity and price of power they can produce and receive, respectively.

Bid-Processing Rules

The rules by which an ISO agent processes bids are listed below.

- Rule A: All bids for supply and demand at the same time must be accepted at the same time.

- Rule B: A demand bid must be met in the market clearing process wholly by supply bids of equal or lesser value.
- Rule C: Supply bids need not be met in their entirety, either at the market clearing point, or at the total demand point. For example, say that two bids to supply power are at the same price, but with different quantities: Q1 = 100 and Q2 = 200. After other bids are met, 90 units are required at this price to satisfy all demand. Both bids are then satisfied in proportion, that is Q1* = (100/300)*90 = 30, while Q2* = (200/300)*90 = 60).

When the market is defined as a "market of last resort", that is, there is no other market available for demand to be met by available supply, the following rule is also incorporated to ensure that demand is met:

- Rule D: After the MCP is determined, all excess demand is met using the unmet portion of the supply bids at the MCP.

How an ISO Processes Bids in an Electric Power Market

The method by which an ISO agent processes bids, according to the above rules, consists of the following steps. An example is included to illustrate the method.

1. The ISO agent receives bids via messages from generation company agents (sellers) and industry company agents (buyers). According to Rule A, the bids are received at the same time. Each bid consists of a price, a quantity, and a type (sell or buy).

   For our example, assume that an ISO received these five bids:

Identifier	Price	Quantity	Bid Type
1	40	15	Buy
2	30	10	Sell
3	50	10	Buy
4	60	5	Buy
5	50	30	Sell

2. The ISO agent then sorts the bids into supply (sell) and demand (buy), and rank-orders the bids based on price. The sell bids are ranked in increasing order; the buy bids are ranked in decreasing order.

   For our example, the following represents the sample rank-ordered bids by sell and buy.

   Bids to sell:

Identifier	Price	Quantity	Bid Type
2	30	10	Sell

Identifier	Price	Quantity	Bid Type
5	50	30	Sell

Bids to buy:

Identifier	Price	Quantity	Bid Type
4	60	5	Buy
3	50	10	Buy
1	40	15	Buy

3. The ISO agent then determines what the minimum MCP is going to be. According to Rule B, a demand bid must be met in the market clearing process wholly by supply bids of equal or lesser value. And as the market of last resort, the entire demand quantity (total of all buy bids) must be met.

   For each buy bid in the list, beginning with the highest bid:

   a) The agent determines whether there is sufficient quantity in the sell list at a price lower than this buy bid that will satisfy the buy bid quantity. If not, the agent has reached a point of decision making. The agent looks at the sell list to answer this question.

      For our example, the ISO agent asks: Are there are at least 5 units available for sale at 60 dollars or less (buy bid 4, the highest price buy bid)? Examining our sell list, we see that, yes, there are 40 (10 + 30) units that can be sold for less than 60 dollars.

Identifier	Price	Quantity	Bid Type
2	30	10	Sell
5	50	30	Sell

   b) If the sell list indicates that there is sufficient quantity to meet the requirements in step 3a above, then the ISO agent marks off the particular bid from the buy list. This is true because it can be satisfied and then attempts to meet that demand by traversing the sell list from lowest to highest price, subtracting the quantity that can be filled from the bids in the sell list.

      For our example, the agent marks off the buy bid that can be satisfied and subtracts 5 units from the lower-priced bid. Now there are 35 units of power (of the original 40) remaining to sell.

   Bids to sell:

Identifier	Price	Quantity	Bid Type	Remaining Quantity 1

Identifier	Price	Quantity	Bid Type	Remaining Quantity 1
2	30	~~10~~	Sell	5
5	50	30	Sell	30
Total Remaining				35

Bids to buy:

Identifier	Price	Quantity	Bid Type	Bid Status
4	60	5	Buy	satisfied
3	50	10	Buy	
1	40	15	Buy	

Note: Step 3 repeats until the requirements of fulfilling the demand can no longer be met. We will follow our example, however, to show how the process continues until that point is reached.

In our example, the agent then moves to the next lowest bid in the buy list and again asks the question posed in step 3a above—whether there is quantity to sell at this price or less that is at least the quantity of the buy bid.

For our example, the ISO examines buy bid 3 and asks if there are at least 10 units available for sale at 50 dollars or less? Examining our sell list, we see that, yes, there are 5 units available at 30 dollars and another 30 available at 50 dollars.

Then, per step 3b, the agent marks off the buy bid that can be satisfied and subtracts the remaining 5 units from the lower-priced sell bid and 5 units from the next sell bid. Now there are 25 units of power (of the original 40) remaining to sell.

Bids to sell:

Identifier	Price	Quantity	Bid Type	Remaining Quantity 1	Remaining Quantity 2
2	30	~~10~~	Sell	~~5~~	0
5	50	30	Sell	~~30~~	25
Total Remaining				35	25

Bids to buy:

Identifier	Price	Quantity	Bid Type	Bid Status
4	60	5	Buy	satisfied
3	50	10	Buy	satisfied

Identifier	Price	Quantity	Bid Type	Bid Status
1	40	15	Buy	

Repeating step 3a, the agent looks at the remaining bid in the buy list, 15 units at 40 dollars, and again asks the question—whether there is quantity to sell at this price or less that is at least the quantity of the buy bid.

For our example, however, now the answer is no. Though there are 25 units available to sell (sell bid 5), these units are priced at 50 dollars each. Thus, sell bid 5 is not going to work and we have reached the point where we can determine the market clearing price (see step 4).

4. To determine the MCP, the ISO agent takes the average of the price of the last successful sell bid and the last successful buy bid.

   Thus, for our example, (50 + 50)/2 = 50 = MCP.

   Effectively then, for our example, all demand for power that is bid at or above the MCP will be met; only buy bid 1 will not be met. However, for the sake of example, let us define this as a market of last resort. In this case, our work is not yet done, as the demand in buy bid 1 is unmet. The ISO agent therefore implements Rule D. As a market of last resort, each industry agent (including the agent that submitted buy bid 1) will receive the quantity of power it requested at a price of 50 dollars per unit. As a result, the generation company agent that submitted sell bid 2 will be notified to produce 10 units and will be paid 50 dollars per unit. The generation company agent that submitted sell bid 5 will be notified to produce 30 units (for the 5 units under Rules A through C as outlined above, plus an additional 25 units under Rule D to satisfy the demand of buy bid 1) and will also be paid 50 dollars per unit.

Bids to sell:

Identifier	Price	Quantity	Bid Type	Remaining Quantity 1	Remaining Quantity 2	Remaining Rule D
2	30	~~10~~	Sell	~~5~~	0	0
5	50	30	Sell	~~30~~	~~25~~	10
Total Remaining				35	25	10

Bids to buy:

Identifier	Price	Quantity	Bid Type	Bid Status
4	60	5	Buy	satisfied
3	50	10	Buy	satisfied

Identifier	Price	Quantity	Bid Type	Bid Status
1	40	15	Buy	satisfied per rule D

Note: When supply (sell) bids are submitted at the same price, but different quantities, the bids are satisfied in proportion, per Rule C.

About Price Caps

An ISO agent's acceptance of bids from generation company agents may be impacted by a price cap placed on the market. This cap is implemented via user input and is in effect for the duration of the run. When a bid is higher than the price cap, the ISO will not accept the bid. Agents responsible for the supply (i.e., GenCo agents) and demand (i.e., industry agents) of power are made aware of the existence of a cap on a market through examination of the bulletin board agent.

Disaster Agent Rules

The primary role of the single disaster agent in Aspen-EE is to inform the generation company agents in the model when a scheduled power outage begins and ends. A scheduled power outage is a user-defined event, as compared to an unscheduled power outage that results from a fuel shortage during a simulation. When a scheduled power outage occurs, the amount of power available for sale by generation companies is reduced by a certain amount, and thus the power market and the behavior of agents who depend on power are impacted. The characteristics of a scheduled power outage—its start time, duration, and percent loss in generation capacity—are user-defined parameters for the disaster agent class in the input file.

Generation companies notify their end-users when a scheduled outage occurs. The disaster agent only notifies the affected generation company. See **Generation Company Rules** for further information on unscheduled power outages.

Bulletin Board Agent Rules

The bulletin board is a special agent in Aspen-EE. This agent serves as a dynamic contact point through which other agents share and retrieve information on the environment. As shown in Figure 2, examples of information posted on the bulletin board are the demand multiplier for electric power; the daily price of electric power for firm customers; the daily price of commercial, fuel company, and industry products; the wages for all agents that hire employees; and the price cap (if any) within an electric power market. Functionally, the bulletin board diverts some of the message passing that needs to occur between agents and, in effect, speeds up processing time. Note that when the parallel version of Aspen-EE is run, the bulletin board is distributed across multiple processors.

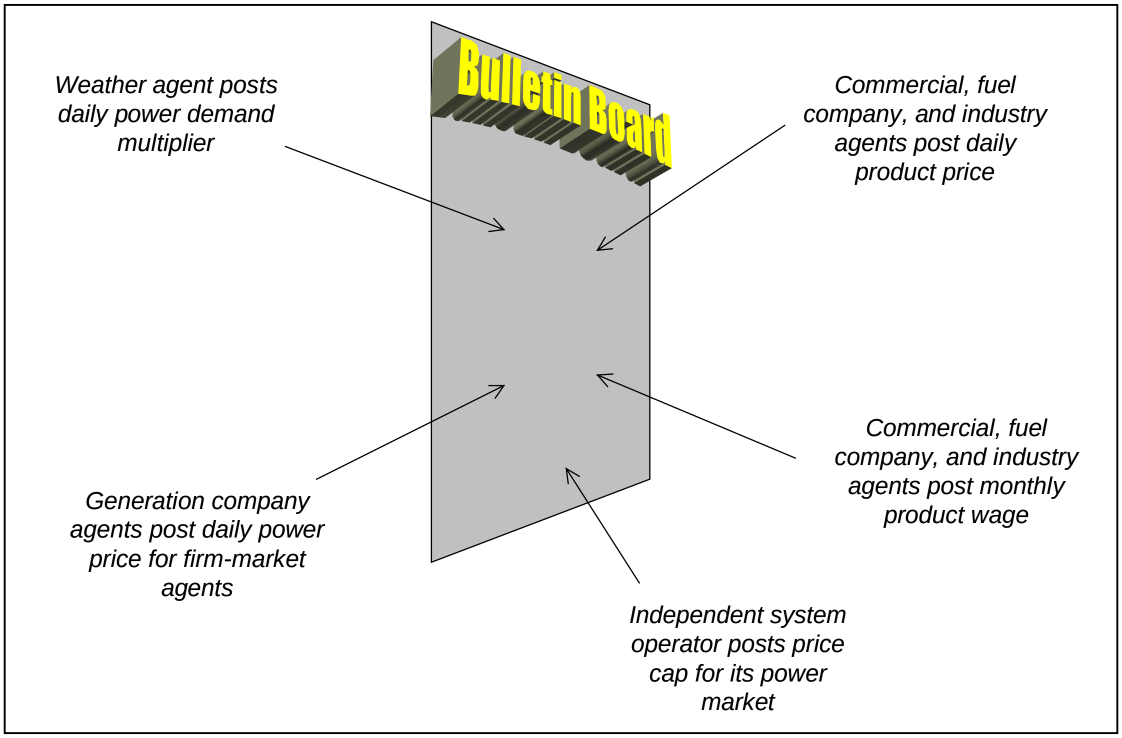

Figure 2. Daily Postings on Bulletin Board.

Weather Agent Rules

The reality of restructuring efforts across the country has revealed the important role that the weather has come to play in the short-term market for electric power. When temperatures cause extremes in the peak level of demand for electricity, the price for obtaining power in this market skyrockets. Similarly, when peak conditions do not exist, customers can meet their demand at or possibly below marginal costs, as generation companies are often willing to sell power under such conditions below the cost of a particular unit so that they can maintain continuous unit operation.

To model the role that temperature plays in the short-term market, Aspen-EE has a weather agent. At the beginning of each Aspen-EE day (in the first time step), this agent determines the demand for electric power and posts the demand on the bulletin board. Industry and generation company agents then retrieve the demand from the bulletin board and use this value (as a multiplier) in their respective bidding calculations to purchase and sell power, respectively. Generation company agents use this data, for example, to first determine how much of their capacity must be held in reserve to meet expected firm demand (from household and government agents, and the like), and therefore cannot be bid into the market.

The demand is represented as a percentage that is relative to the demand for electricity at the mean temperature. For the cases examined in this report, demand ranges from .9 (10 percent less than normal) to 1.3 (30 percent more than normal). The weather agent determines the demand D for the current time t, referred to as $D(t)$, by using the state matrix M1 in Table 5.

Table 5. State Matrix M1 Probabilities

M1	*D(t)*					
	From \ to	.9	1	1.1	1.2	1.3
	.9	.3	.4	.3		
	1	.2	.4	.3	.1	
D(t-1)	1.1	.1	.2	.4	.2	.1
	1.2		.1	.4	.3	.2
	1.3			.4	.4	.2

Matrix M1 allows us to incorporate variability in demand from one time to the next (e.g., day to day). M1 contains a set of probabilities associated with the range of possible demand values. The agent uses the probabilities associated with the demand determined at the previous time, referred to as *D(t-1)*, in determining the demand for the current time, *D(t)*. The agent generates a Uniform (0,1) random number *U*. Then, utilizing the probabilities on the *D(t-1*) row that is labeled with the previous value of *D(t)*, the new value of *D(t)* is generated using the inverse-transform method for discrete random variables, incorporating the value of *U* previously calculated.

An example can help to illustrate this process. Assume that the demand for the previous time, *D(t-1)*, was 1.1 (10 percent above normal). Thus, the weather agent will work with the probabilities on that row (i.e., .1, .2., .4, .2, and .1). In its first action, the weather agent generates a Uniform (0,1) random value $U = 0.454$. Then, the agent sets *D(t)* to 0.9, 1.0, 1.1, 1.2, or 1.3, depending on the subinterval in [0,1] into which *U* falls based on the cumulative distribution function developed from the discrete probabilities on the *D(t-1)* row of the matrix. If $U \leq .1$, then let $D(t) = 0.9$; if $0.1 < U \leq 0.3$, let $D(t) = 1.0$; if $0.3 < U \leq 0.7$, let $D(t) = 1.1$; if $0.7 < U \leq 0.9$, let $D(t) = 1.2$; finally if $0.9 < U$, let $D(t) = 1.3$. Since $U = 0.454$ in this case, the value chosen for *D(t)* will be 1.1.

The example above can also be viewed from a less technical perspective, as follows: Assume that the demand for the previous time, *D(t-1)*, was 1.1 (10 percent above normal). Thus, the weather agent will work with some, or all, of the probabilities on that row (i.e., .1, .2., .4, .2, and .1). In its first action, the weather agent throws a random die that returns a value of .454. Then, the agent compares the probability in the first cell, which is .1, to .454. Since .1 is less than .454, the agent moves to the next cell, which contains a probability of .2. The agent adds the probability in the previous cell to that in the current cell and obtains a value of .3, which it compares to .454. Since .3 is less than .454, the agent moves to the next cell and performs a similar summation and compare operation. This time, the summed value of the three cells, which is equal to .7, is greater than .454. Thus, the agent selects the value for *D(t)* to be 1.1, which is the column header associated with .4.

Note that in the current implementation the demand is only determined once per Aspen-EE day. However, the capability exists to determine demand more frequently because the simulation uses time steps of one hour.

How Electric Power Markets Work

Based on user input, an Aspen-EE run can include one or more electric power markets.The major participants in each such market are one or more generation company (GenCo) agents with a supply of electric power, one or more industry agents with a demand for electric power, and one independent system operator (ISO) agent that processes the bids to buy and sell and determines how the market is to be cleared. The market utilized in Aspen-EE conducts business on a daily basis, and the process begins after GenCo and industry agents acquire information about the temperature from the bulletin board agent which can then be used to estimate demand. Figure 3 depicts a simplified representation of the process in which the major participants engage.

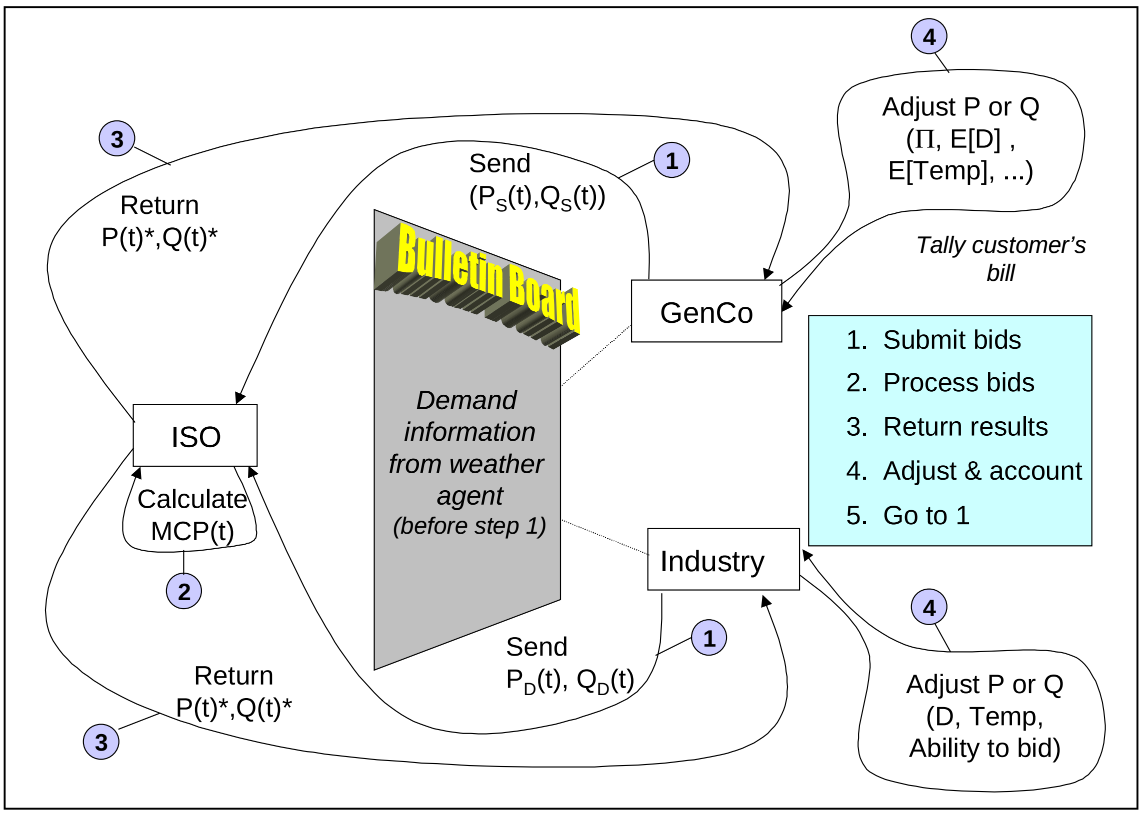

Figure 3. Overview of an Aspen-EE electric power market.

Per step 1, GenCo and industry agents submit pairs of price (P) and quantity (Q) bids to an ISO. The GenCo agents each propose to sell a given quantity of power at a specific price for time t, as represented by $P_S(t),Q_S(t)$. GenCo agents have the potential to submit multiple $P_S(t),Q_S(t)$ pairs to the ISO; this would represent the variety of generation facilities (and the differences in operating costs) owned and operated by a particular GenCo. For the example in the model, however, each GenCo owns a single facility and submits a single bid to the ISO. The industry agents each propose to buy a given quantity of power at a specific price for time t, as represented by $P_D(t),Q_D(t)$. Next, per step 2, the

ISO processes the bids from all GenCo and industry agents to determine the market clearing price (MCP). Once the MCP has been determined, the ISO sends the results back (step 3) to the buyers and sellers. The results consist of the ISO-calculated market clearing quantity (Q*) and MCP (P*) for time t, represented by P(t)*,Q(t)*. The results let each GenCo agent know how much power to produce at time t and the price of that power; it is always possible that a GenCo agent's bid may not be accepted and thus that agent would sell no power at time t. The results also let each industry agent know how much power it will receive and the price it will be charged for that power. The markets defined in this utilization of Aspen-EE are markets of last resort; that is, all demand bids will be met at the market clearing price (MCP) calculated for that market provided there is sufficient supply to meet demand.

Moving now to step 4, we find the GenCo and industry agents evaluating the price and quantity results and adjusting their price and quantity bids for the next time step (day t+1). GenCo agents consider such factors as profit earned in time step t versus what they expected to make, expected temperature for the next time step, and subsequently expected demand for the next time step. Industry agents base their evaluation on factors like change in demand, which is a relative value based on change in temperature, and ability to bid.

Steps 1 through 4 encompass the general activities occurring in the market of last resort during a time step. The process repeats, per step 5, at the next time step for bidding. Every so often, as also noted in Figure 3, GenCo agents will bill customers for the power they have used and the customers will send back payment for their bills. In this context, customers include all agents who are users of electricity though many of these agents are not identified in Figure 3.

For detailed information on the specific rules of behavior in which market participants are engaged, refer back to **How Industry Agents Bid in an Electric Power Market**, **Generation Company Agent Rules**, and **Independent System Operator Rules**.

Results and Analysis

For this work we examine five scenarios. This section presents the initial run conditions and provides an analysis of the results.

Run Conditions

In each scenario we consider two important conditions: 1) the number of electric power markets and 2) whether or not the independent system operators (ISOs) operate each market with or without a price cap. Table 6 summarizes these conditions across the five scenarios.

Table 6. Scenario Conditions

Scenario	Number of Markets	Cap on Market 1	Cap on Market 2
1	2	No	No
2	2	No	Yes
3	2	Yes	Yes
4	1	No	--
5	1	Yes	--

Simulations using the model were run with the following agents:

- 2 ISO agents (in the two-market case) and 1 ISO agent (in the one-market case)
- 6 industry agents (in the two-market case, three industry agents are committed to buy from each market)
- 725 household agents
- 2 generation company agents
- 1 commercial agent
- 1 weather agent
- 1 fuel company agent
- 1 government agent
- 1 bulletin board agent

Each ISO agent operates a single daily market for power, which operates as a market of last resort. Note that a scheduled power outage was not considered in the scenarios examined. Note also, that scenarios 4 and 5 are single power market cases.

Analysis

Some of the most economically interesting observations are gathered from an examination of those scenarios developed that involve multiple markets. We first examine Scenario 1, which contains two markets for electric power (see Figure 4). For this scenario, neither market is under a price cap. As can be seen, both markets share similar patterns over time for the value of the market clearing price (MCP). The MCP of market 2 is consistently higher than that of market 1. Buyers and sellers of power face identical rules in determining their price bids, but those confined to market 2 (specifically, the industries buying power from market 2) begin with a higher mean bid value Pbar, and therefore have a higher bidding trend than those bidding into market 1. This leads to the consistently higher MCP in market 2 for this scenario.

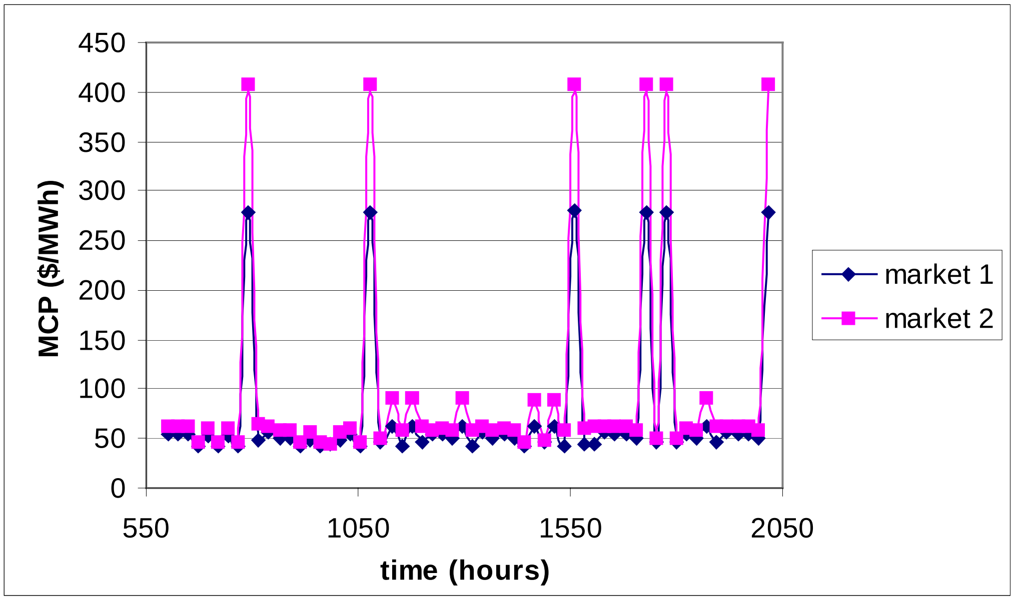

Figure 4. MCP, markets 1 and 2 vs. time, Scenario 1.

For Scenario 2 (where market 2 has a price cap while market 1 does not), the same condition holds except for those rare occasions when the demand multiplier $D(t)$ is high. In these cases, the prices in market 1 are nearly identical to those seen under Scenario 1; but in market 2, the capped market, the price reaches the cap only (as shown in Figure 5 below).

Scenario 3 (where both markets have identical price caps) brings a very different picture. Whereas in Scenarios 1 and 2 the MCP in market 2 was typically higher than that in Market 1, here we have a reversal. The MCP in market 1 is consistently higher than in market 2 (see Figure 6). There are two direct causes for this behavior. As shown in Figure 7, the MCP for market 1 is appreciably higher under the price cap than it was without the price cap, with the notable exception of those times when price spikes occurred in conjunction with high demand when the market had no price cap. These exceptions are offset by a consistent increase in prices under the price cap, regularly running 12 to 15 percent higher than the MCP without the price cap. The second cause is a consistent decline in the MCP of market 2, on the order of 10 to 30 percent under the price cap (see Figure 8).

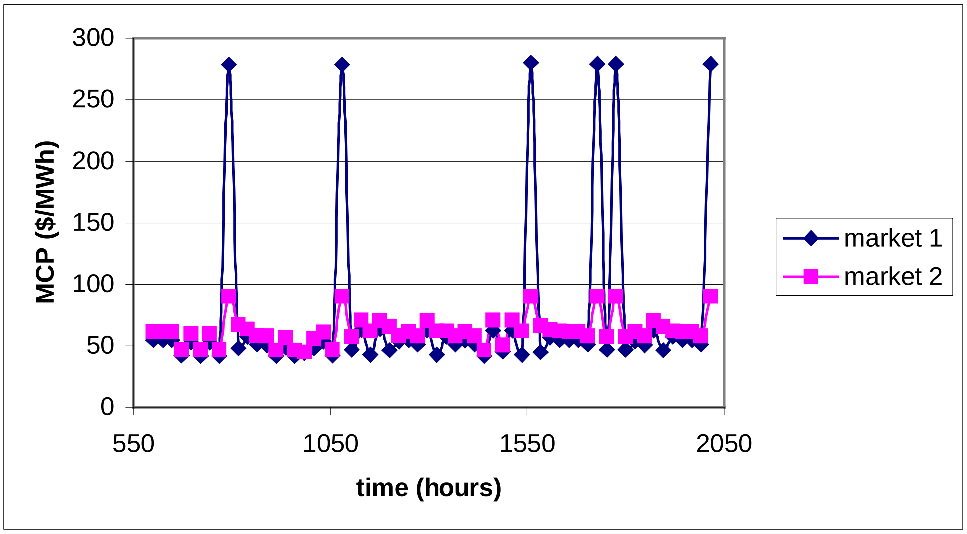

Figure 5. MCP, markets 1 and 2 vs. time, Scenario 2.

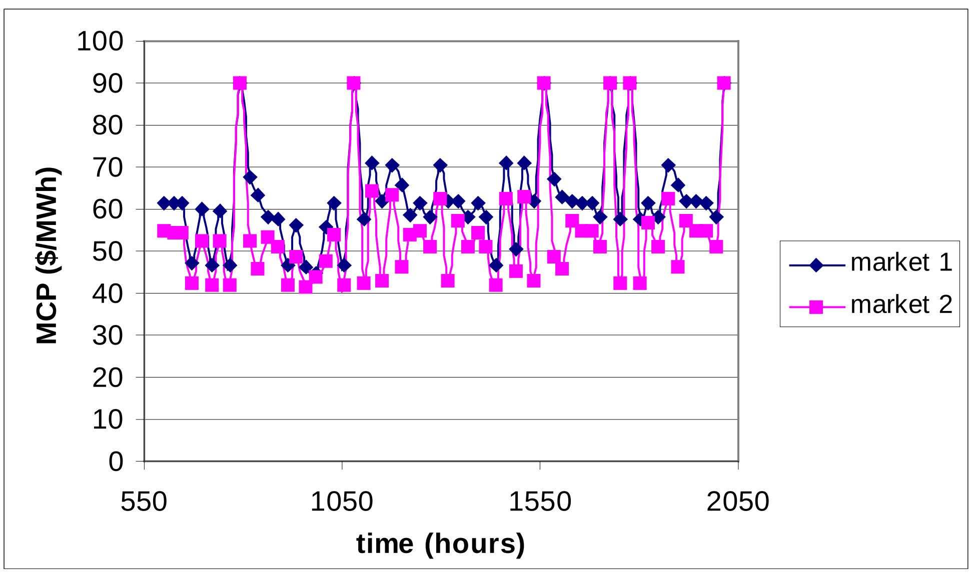

Figure 6. MCP, markets 1 and 2 vs. time, Scenario 3.

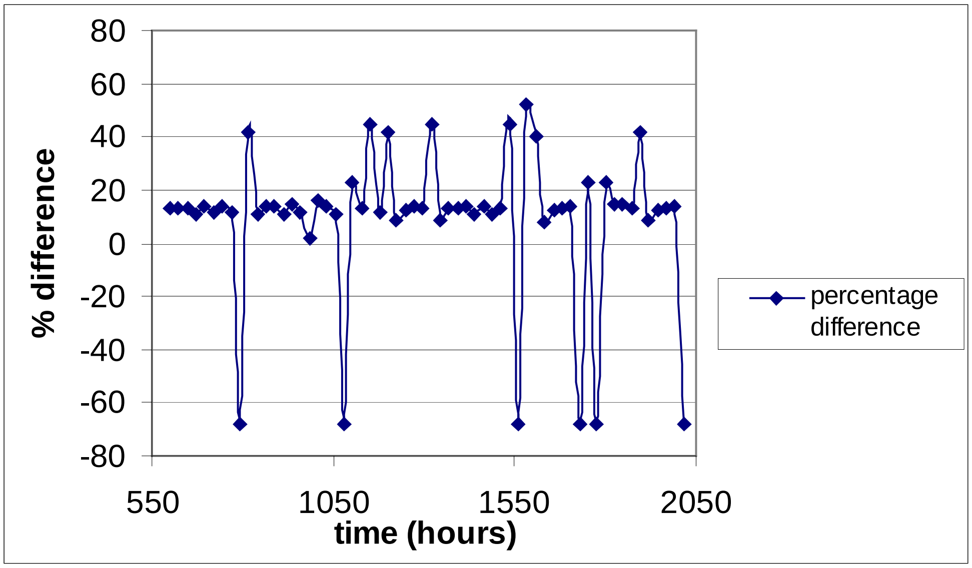

Figure 7. Percentage difference in MCP for market 1 between Scenarios 1 and 3 vs. time.

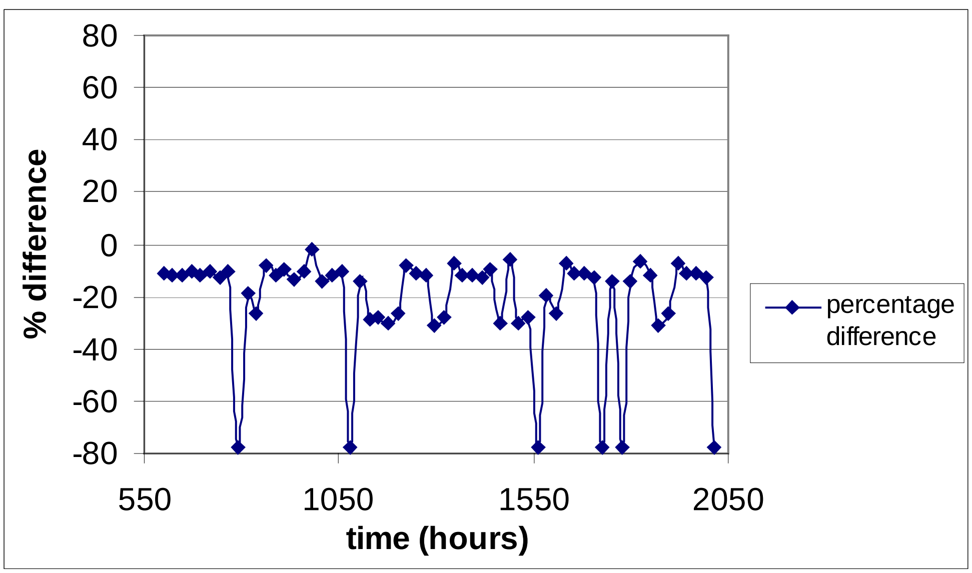

Figure 8. Percentage difference in MCP for market 2 between Scenarios 1 and 3 vs. time.

This behavior on the part of both markets in Scenario 3 (when both markets are capped at the same price) is consistent with expected economic behavior. Market 1, traditionally the market that results in a lower MCP without price caps, faces an increase in price, as this market is a price leader under the rules of Scenario 1. Market 2, on the other hand, has a consistently smaller demand and higher prices when no price caps are present. The natural trend of these two markets to move towards a similar price given their identical price caps is present in this behavior. Note well that market 2 has little to no change in its behavior until a price cap is instituted for market 1 (see Figure 9). This behavior is similar to that seen in the single-market scenarios (4 and 5). Little difference is seen in the actual MCP with and without the price cap, nor in the relative MCP, with the exception of those times when the price cap is hit in the capped market (see Figures 10 and 11). Each generation company (GenCo) also experiences declining revenue as new price caps are added to the markets (see Figures 12 and 13). But this is not the only behavior seen on the part of the GenCos as the market rules change from scenario to scenario. GenCo 1 is quite decisive in its decision to divide its available capacity between the two markets, and quite consistent from scenario to scenario, maximizing its play into market 1. On the other hand, GenCo 2 is stuck in a quandary in each of the scenarios; its commitment to any one market never exceeds 55 percent, and is in a constant state of change. The reasons for these two actions are simple. GenCo 1, with a lower marginal cost of operation than GenCo 2, is able to act as the dominant player in whichever market it thinks will yield it the greatest profit. Following a brief period in which GenCo 1 learns which of the markets will yield it maximum profit, it decides to maximize its bid quantity into market 1. GenCo 2, with higher operating costs, is left to try and fill in remaining demand in cases where GenCo 1 is unable to satisfy both markets. Often, its sales in one (or both markets) is zero. GenCo 2 manipulates its bid quantities, increasing share of capacity to a market in which it has just filled demand, in an attempt to satisfy more, but because of its disadvantage in marginal cost in comparison to GenCo 1, GenCo 2 will always serve as the “follower.”

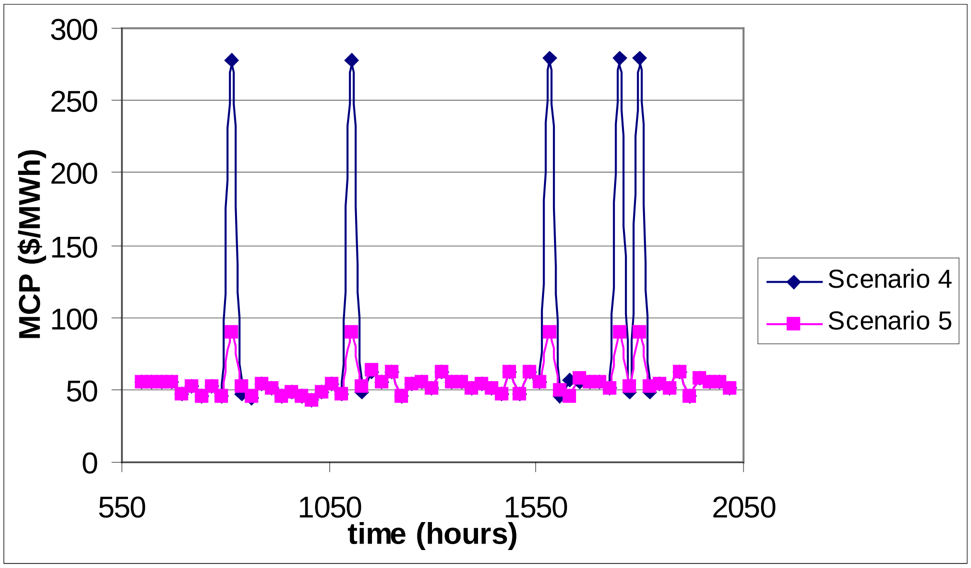

Figure 9. Percentage difference in MCP for market 2 between Scenarios 1 and 2 vs. time.

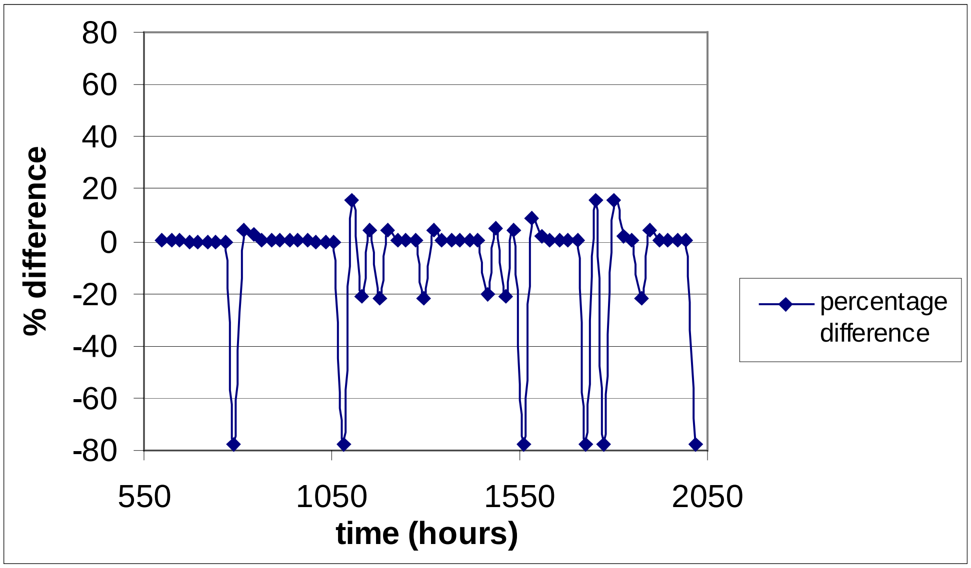

Figure 10. MCP for single market, Scenarios 4 (uncapped) and 5 (capped) vs. time.

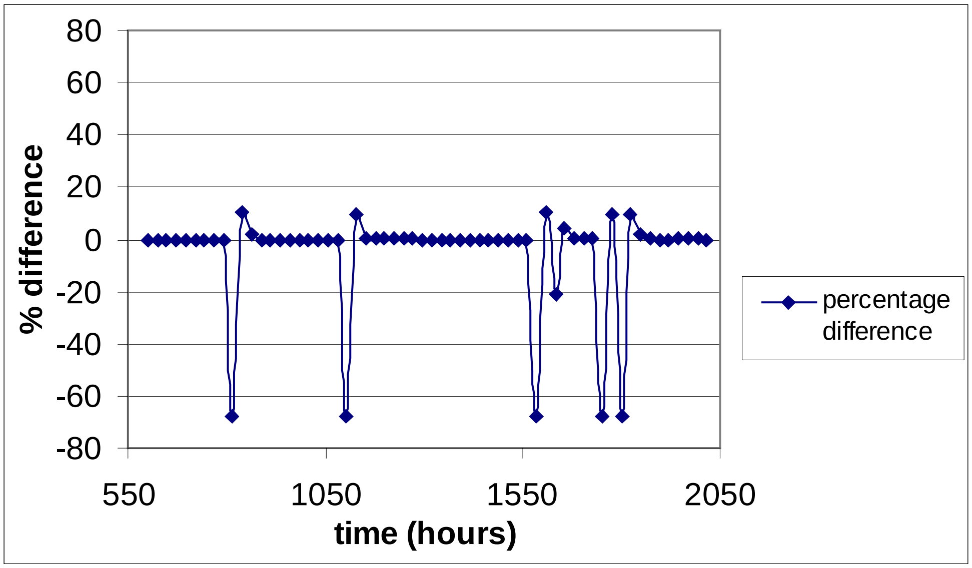

Figure 11. Percentage difference in MCP for single market between Scenarios 4 and 5 vs. time.

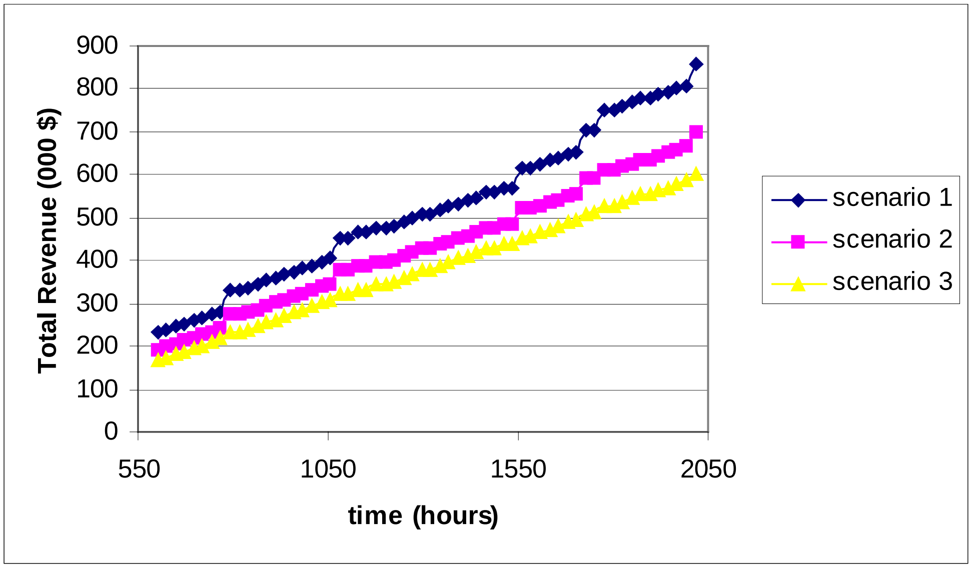

Figure 12. GenCo 1 total revenue (000 $) vs. time, Scenarios 1–3.

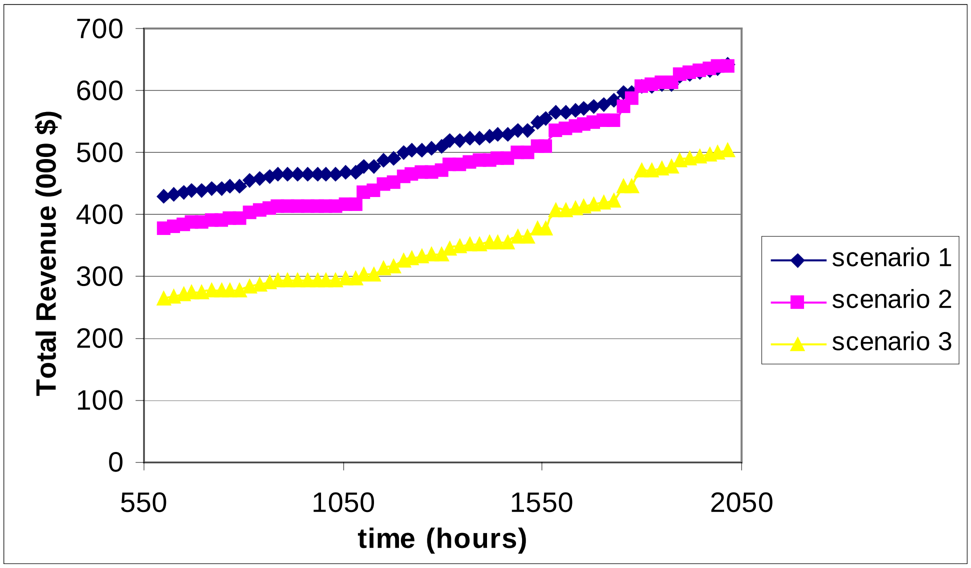

Figure 13. GenCo 2 total revenue (000 $) vs. time, Scenarios 1–3.

Combined, these results show the potential of Aspen-EE to examine market issues including market power and understanding of the effects of market rules on participant behavior.

Applications and Future Plans

Our previous discussion of the results for the sample power-market scenarios points out how Aspen-EE can be applied to examine the economic costs of policy decisions, like price caps, on the short-term trading of electric power. Aspen-EE power markets consider the business constraints on generation companies and ISOs—unlike other models for the electric utility industry that focus on the physical system. Aspen-EE power markets also feature a gaming capability, not found in other utility models, that permits us to look behind the scenes and discover how individual generation companies can use their pricing knowledge to their own economic advantage, including possible collusive behavior. Users concerned with understanding how market players during this time of major industry restructuring may attempt to game the market will find Aspen-EE particularly helpful in testing a particular set of market rules before these rules are actually put into place.

Though not investigated in the sample scenarios, Aspen-EE can also be used to explore more widespread vulnerabilities in the economy such as shifts in product and labor markets that might occur when governmental policies coupled with generation company choices result in disruptions such as power outages. Again, Aspen-EE offers a capability not available in current utility models. Most outage analysis is conducted on small samples after an outage has occurred and is based, at best, on estimates of amounts spent during the outage. Aspen-EE can provide calculated results of possible losses during an outage that has yet to occur.

A number of other enhancements are also envisioned. One such upgrade relates to the aggregation of demand for electric power in support of larger-scale modeling efforts. For example, we intend to aggregate household agents into neighborhoods; currently the demand for electric power of each household agent is considered individually. Another upgrade focuses on the addition of a new role for government so that this agent could make decisions on whether or not restructuring should take place, and in what form. The current version of Aspen-EE assumes a restructured environment. A third potential upgrade concerns the addition of other markets for the trading of power, such as day of/hour ahead, month-ahead, and hour-ahead, where the criterion for satisfying demand is only up to the level that demand was requested. Currently, the power markets in Aspen-EE satisfy all demand.

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Appendix A
Aspen-EE Input File

This appendix describes the contents of the user-prepared input file to Aspen-EE. Examples of initial values are given for all parameters listed. The set of initial values, however, was not used for the scenario runs discussed in this report.

Section One – Problem Specification Data

The first section of the input file contains general information on the problem. The number of each type of agent in the problem is specified, as well as the edit frequency used to print agent information to an output file.

Name	**Description**	**Example**
Job Name	Any user-specified information that describes the problem	“Aspen-EE Test”
User Name	Any user-specified name that defines the user	“Eric Eidson”
Run Comments	Any description to define run conditions of the problem	“power outage occurs at time step 2000”
Pause Time	Total number of time steps, i.e., hours in the problem	2016
Snapshot Frequency	Edit frequency for printing data to an output file	1 = every time step
Random Seed	Random number seed	65535
Create	Number of individual agents and an agent class name that defines the agent population in the problem	425 Household 10 Industry 1 Weather

Section Two – Agent Data

This section contains information on the parameters that need to be specified for each agent class in the problem. Any number of agents of any number of agent classes may be specified. Parameters can either be specified as a single value or as a range. Ranges allow Aspen-EE to create agents that have some variations instead of being identical copies.

Household Class Data

Name	**Description**	**Example**
Number of Adults	Used to calculate household consumption products	1 – 4
Number of Children	Used to calculate household consumption of products	0 – 4
Tax Rate	Income tax rate	10 percent
Savings	Initial dollar amount in savings	1000 – 5000 dollars
Probability Exponent	Value of the exponent used to determine from which industrial or commercial firm the household will purchase product	8
Unemployed Need Fraction	Reduction in need for industrial or commercial products when unemployed	.75
Need Decay Fraction	Rate at which the need for industrial or commercial products decays during period that the product cannot be purchased (i.e. product shortage)	.50
Outage Need Reduction	Reduction in need for industry or commercial products during a power outage	.5
Salary Factor	Multiplier used to determine the salary desired when seeking higher-paying jobs	1.5
Electricity Demand	Power used per day	1.0 megawatts (MW)

Industry Class Data

Name	**Description**	**Example**
Employee Wage	Initial worker wage rate	75.00
Tax Rate	Income tax rate	10 percent
Cash Assets	Initial amount of cash held by the agent	1000 dollars
Productivity Rate	Worker productivity	3.0
Product Price	Initial product price	3.00 dollars
Inventory	Initial product inventory	4000.0 units
Minimum Days Inventory	Inventory quantity that indicates additional workers are needed	20.0
Maximum Days Inventory	Inventory quantity that indicates fewer workers are needed	40.0
Employee Increase Factor	Factor used to determine the number of employees desired when hiring	1.10
Employee Decrease Factor	Factor used to determine the number of employees desired when firing	.90

Name	Description	Example
Short Lag	Number of days used in determining the average short-term market price	5.0 days
Long Lag	Number of days used in determining the average long-term market price	10.0 days
Cost Per Unit	Cost of production per unit produced	1.0 dollars
Electricity Price Request	Initial price request per MW for power	65.0
Electricity Demand	Power used per day	40.0 MW
Outage Productivity Reduction	Productivity reduction during a power outage	.5
Price Multiplier Matrix	Matrix of values for the price multiplier given the weather	[0.3, 0.0, 0.1, 0.9, 9.0]

<u>Commercial Class Data</u>

Name	Description	Example
Employee Wage	Initial worker wage rate	75.00
Tax Rate	Income tax rate	10 percent
Cash Assets	Initial amount of cash held by the agent	1000 dollars
Productivity Rate	Worker productivity	3.0
Product Price	Initial product price	28.00 dollars
Inventory	Initial product inventory	4000.0 units
Minimum Days Inventory	Inventory quantity that indicates additional workers are needed	20.0
Maximum Days Inventory	Inventory quantity that indicates fewer workers are needed	40.0
Employee Increase Factor	Factor used to determine the number of employees desired when hiring	1.10
Employee Decrease Factor	Factor used to determine the number of employees desired when firing	.90
Short Lag	Number of days used in determining the average short-term market price	5.0 days
Long Lag	Number of days used in determining the average long-term market price	10.0 days
Cost Per Unit	Cost of production per unit produced	1.0 dollars
Electricity Demand	Power used per day	60.00 MW
Outage Productivity Reduction	Productivity reduction during a power outage	.2
Outage Inventory Reduction	Amount of inventory lost during a power outage	.2

GenCo (Generation Company) Class Data

Name	Description	Example
Static Usage	Power demand per customer for the firm market	1.0 per day
Firm Price	Price for power on the firm market	1.0 dollars
Cash Assets	Initial cash assets owned by the generation company	10000 dollars
Fuel Need	Fuel needed per unit of power produced	.005 fuel units
Supply Need	Industrial supplies needed per unit of power produced	.01 industrial units
Capacity	Generation capacity	600 MW
Marginal Operating Cost	Marginal operating cost	35 dollars
Desired Margin	Amount of profit desired over margin	.2
Price Multiplier	Multiplier used to increase price bids	1.20
Supplies	Current amount of industrial product owned by the generation company	100.0 units
Desired Supplies	Minimum amount of industrial product inventory desired by the generation company	100.0 units
Desired Supply Excess	Amount of supply ordered in excess of the minimum desired inventory per order	125.0 units
Probability Exponent	Value of the exponent used to determine from which industry the generation company will purchase product	8
Desired Fuel	Minimum amount of fuel inventory desired by the generation company	500.0 fuel units
Fuel Supply	Current amount of fuel owned by the generation company	100.0 fuel units
Desired Fuel Excess	Amount of fuel ordered in excess of the minimum desired inventory per order	25.0 fuel units

FuelCo (Fuel Company) Class Data

Name	Description	Example
Employee Wage	Initial worker wage rate	75.00
Tax Rate	Income tax rate	10 percent
Cash Assets	Initial amount of cash held by the agent	1000 dollars
Productivity Rate	Worker productivity	3.0
Product Price	Initial product price	28.00 dollars

Name	Description	Example
Inventory	Initial product inventory	50.0 fuel units
Minimum Days Inventory	Inventory quantity that indicates additional workers are needed	20.0 fuel units
Maximum Days Inventory	Inventory quantity that indicates fewer workers are needed	40.0 fuel units
Employee Increase Factor	Factor used to determine the number of employees desired when hiring	1.10
Employee Decrease Factor	Factor used to determine the number of employees desired when firing	.90
Short Lag	Number of days used in determining the average short-term market price	5.0 days
Long Lag	Number of days used in determining the average long-term market price	10.0 days
Electricity Demand	Power used per day	1.0
Outage Productivity Reduction	Productivity reduction during a power outage	.5

Weather Class Data

Name	Description	Example
Demand Multiplier	Factor to change demand	1.1
State Transition Matrix	Matrix of probabilities to change demand multiplier	[0.5 0.5 0.5 0.5]

Disaster Class Data

Name	Description	Example
Start Time	Starting time of power outage	10008 time step
Duration	Duration of power outage	24 hours
Generator Capacity Loss	Percent of power generation lost during outage	25 percent

ISO Class Data

Name	Description	Example
Price Cap	Maximum price bid allowed to power sellers	90.00 dollars

<u>Government Class Data</u>

Name	Description	Example
Benefit	Starting time of power outage	10008 time step
Cash Asset	Duration of power outage	24 hours
Electricity Price Request	Initial price request per MW for power	50.0
Electricity Demand	Initial price request per MW for power	1.0 MW
Outage Cash Reduction	Percentage of cash that remains after a power outage	0.9

Appendix B

A Demonstration of Infrastructure Disruption

A demonstration version of the original Aspen model is available on the World Wide Web for anyone interested in observing infrastructure vulnerabilities. This version can simulate the impact of an infrastructure disruption (such as a telecommunications or power outage) on the rest of the economy. The user defines both the portion of the economy to be affected and the duration of the disruption period. Figure B-1 depicts results based on the examination of several cases using this model.

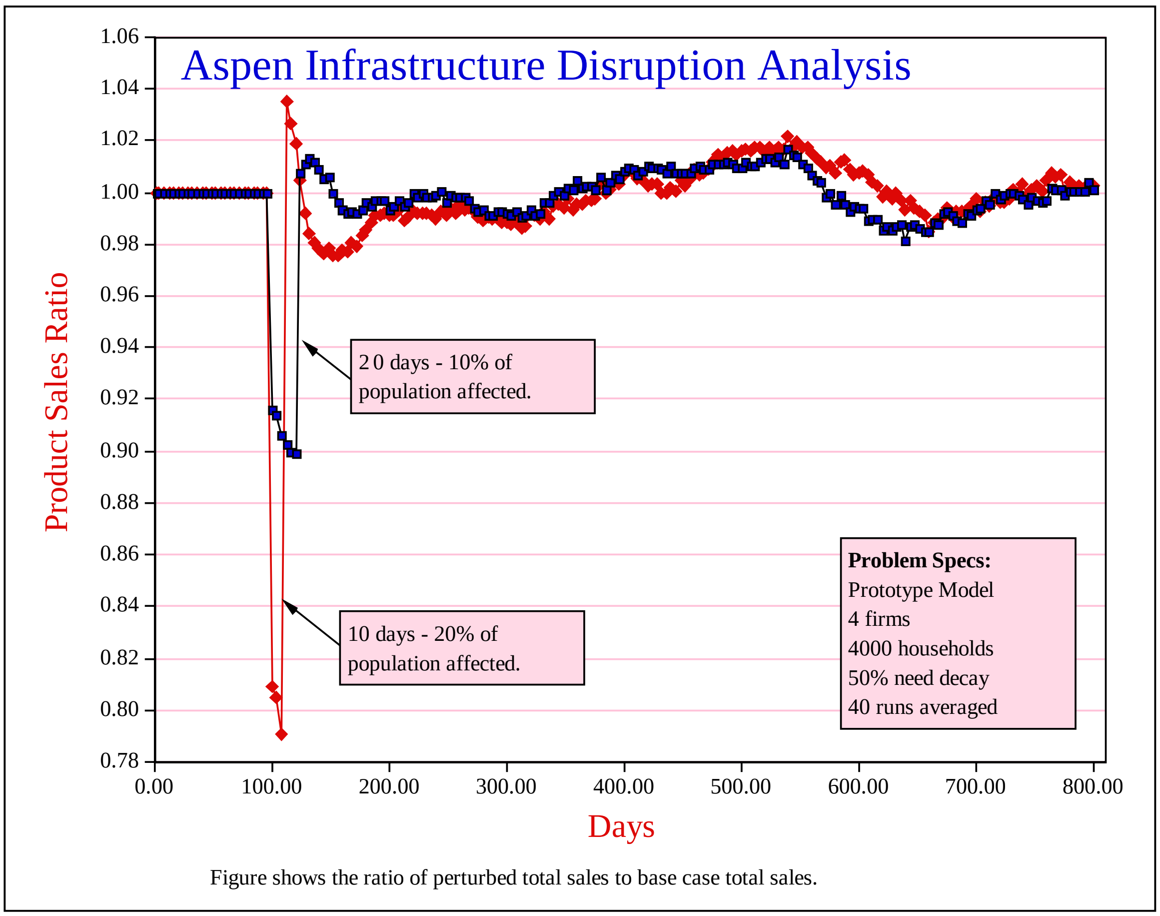

Figure B-1. Ratio of product sales in disruption case to product sales in 'base' case vs. time for disruption cases of varying size and duration utilizing Aspen demonstration model.

This figure specifically examines the effects of a pair of sample disruptions on product sales in comparison to a 'base' case in which no disruption takes place. In one of the disruption cases, a 10-day disruption prevents 20 percent of the population from making purchases from firms. In the other disruption case, a smaller percentage of the population (in this case 10 percent) is affected for a longer period of time (20 days). Relative to the 'base' case, both of the disruptions lead to a short-term decline in the relative level of product sales, essentially for the duration of the disruption event. The relative level of decline increases as the length of the duration increases. In both of the disruption cases, this is then followed by a short-term increase in demand relative to the ‘base’ case. An oscillation sequence continues for quite some time for each of these disruption cases, with relative sales varying plus or minus 2 percent relative to the ‘base’ case. For instructions on running the demonstration model, go to http://www-aspen.cs.sandia.gov/aspen.html.

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